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MILITARY HANDBOOK

METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES

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FOREWORD

1. This military handbook is approved for use by all Departments and Agencies of the Department of Defense and the Federal Aviation Administration.

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Chairman, MIL-HDBK-5 Coordination Activity (937-656-9134 voice, 937-255-4997 fax), AFRL/MLSC, 2179 Twelfth St., Room 122, Wright-Patterson AFB, OH 45433-7718, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of Chapter 1 or by letter if using the hard copy.

3. This document contains design information on the strength properties of metallic materials and elements for aerospace vehicle structures. All information and data contained in this handbook have been coordinated with the Air Force, Army, Navy, Federal Aviation Administration, and industry prior to publication, and are being maintained as a joint effort of the Department of Defense and the Federal Aviation Administration.

4. The electronic copy of the Handbook is technically consistent with the paper copy Handbook; however, minor differences exist in format, i.e., table or figure position. Depending on monitor size and resolution setting, more data may be viewed without on-screen magnification. The figures were converted to electronic format using one of several methods. For example, digitization or recomputation methods were used on most of the engineering figures like typical stress-strain and effect of temperature, etc. Scanning was used to capture informational figures such as those found in Chapters 1 and 9, as well as most of the S/N curves and the majority of graphics in Chapters 4 through 7. These electronic figures were also used to generate the paper copy figures to maintain equivalency between the paper copy and electronic copy. In all cases, the electronic figures have been compared to the paper copy figures to ensure the electronic figure was technically equivalent. Appendix E provides a detailed listing of all the figures in the Handbook, along with a description of each figure's format.

Custodians:
Army—AV
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FAA

Preparing activity:
Air Force: 11

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Army—ME, MI
Navy—CG
Air Force—80, 82, 84, 99

EXPLANATION OF NUMERICAL CODE

For chapters containing materials properties, a deci-numeric system is used to identify sections of text, tables, and illustrations. This system is explained in the examples shown below. Variations of this deci-numerical system are also used in Chapters 1, 8, and 9.

<u>Example A</u> 2.4.2.1.1

General material category (in this case, steel) . . . .

A logical breakdown of the base material by family characteristics
(in this case, intermediate alloy steels); or for element properties . . . .

Particular alloy to which all data are pertinent. If zero, section contains comments
on the family characteristics . . . .

If zero, section contains comments specific to the alloy; if it is an integer, the
number identifies a specific temper or condition (heat treatment) . . . .

Type of graphical data presented on a given figure
(see following description) . . . .

<u>Example B</u> 3.2.3.1.X

Aluminum . . . .

2000 Series Wrought Alloy . . . .

2024 Alloy . . . .

T3, T351, T3510, T3511, T4, and T42 Tempers . . . .

Specific Property as Follows . . . .

Tensile properties (ultimate and yield strength) 1

Compressive yield and shear ultimate strengths 2

Bearing properties (ultimate and yield strength) 3

Modulus of elasticity, shear modulus 4

Elongation, total strain at failure, and reduction of area 5

Stress-strain curves, tangent-modulus curves 6

Creep 7

Fatigue 8

Fatigue-Crack Propagation 9

Fracture Toughness 10

CONTENTS

NOTE: Information and data for alloys deleted from MIL-HDBK-5 may be obtained through the Chairman, MIL-HDBK-5 Coordination Activity.

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Appendices

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CHAPTER 1

GENERAL

1.1 PURPOSE, PROCUREMENT, AND USE OF DOCUMENT

1.1.1 INTRODUCTION — Since many aerospace companies manufacture both commercial and military products, the standardization of metallic materials design data, which are acceptable to Government procuring or certification agencies is very beneficial to those manufacturers as well as governmental agencies. Although the design requirements for military and commercial products may differ greatly, the required design values for the strength of materials and elements and other needed material characteristics are often identical. Therefore, this publication is to provide standardized design values and related design information for metallic materials and structural elements used in aerospace structures. The data contained herein or from approved items in the minutes of MIL-HDBK-5 coordination meetings are acceptable to the Air Force, the Navy, the Army, and the Federal Aviation Administration. Approval by the procuring or certificating agency must be obtained for the use of design values for products not contained herein.

This printed document is distributed by the Defense Area Printing Service (DAPS). It is the only official form of MIL-HDBK-5. If computerized MIL-HDBK-5 databases are used, caution should be exercised to ensure that the information in these databases is identical to that contained in this Handbook.

A copy of this Handbook can be requested by mail or FAX on company letterhead, showing the complete mailing address and point of contact. Assistance in ordering may be obtained by calling (215) 697-2179. The FAX number is (215) 697-1462.

Alternatively, the DD Form 1425, enclosed on page 1-43, may be filled out and mailed to:

DODSSP
700 Robbins Avenue Bldg 4D
Philadelphia, PA 19111-5094.

1.1.2 SCOPE OF DOCUMENT — This document is intended primarily as a source of design allowables, which are those strength properties of metallic materials and elements (primarily fasteners) that are widely used in the design of aerospace structures. These metallic materials include all systems potentially useful in aerospace and aircraft applications, including those involving reinforcing components. This document also contains information and data for other properties and characteristics, such as fracture toughness strength, fatigue strength, creep strength, rupture strength, fatigue-crack propagation rate, and resistance to stress corrosion cracking. The use of this type of information is not mandatory. Those properties presented as design allowables are listed as A-, B-, or S-basis values (see Section 1.4.1.1 for definition of basis). Data for other properties are presented as typical. The materials included in this document are standardized with regard to composition and processing methods and are described by industry or government specifications. When needed design allowables are not available in this document, the procuring or certifying government agency should be contacted to determine data requirements and documentation, which may be required to justify design values used by the aerospace company.

In addition to the properties of the materials and elements themselves, there are contained herein some of the more commonly used methods and formulas by which the strengths of various structural elements or components are calculated. In some cases, the methods presented are empirical and subject to further refinements. Any further expansion of information on element behavior in MIL-HDBK-5 will emphasize those material characteristics needed to assist the design function. Methods of structural analysis are not within the scope of this document.

Where available, applicable references are listed at the end of each chapter. The reference numbers correspond to the paragraph to which they most generally apply. References are provided for guidance to further information on a particular subject, but since data therein may not have met the guidelines criteria of Chapter 9, such material is not to be considered approved by virtue of its listing.

1.1.3 USE OF DESIGN MECHANICAL PROPERTIES — It is customary to assign minimum values to certain mechanical properties of materials as procurement specification requirements. In the absence of acceptable statistical data, the design mechanical properties given herein are based on these minimum values (see S-Basis in Section 1.4.1.1). The manner in which these design mechanical properties are to be used will depend on the type of structure being considered and will be specified in the detailed structural requirements of the procuring or certificating agency. The use of the different design mechanical properties, such as ultimate tensile strength, yield strength, etc.; the factors of safety associated with them; and the arbitrary reductions in allowable stresses (which may be in the nature of specific requirements, or may be considered necessary in particular cases); will not be taken up in detail since information of this sort does not affect the material properties as such.

1.2 SYMBOLS, ABBREVIATIONS, AND SYSTEMS OF UNITS

1.2.1 SYMBOLS AND ABBREVIATIONS — The symbols and abbreviations used in this document are defined in this section with the exception of statistical symbols. These latter symbols are defined in Appendix A.

A	Area of cross section, square inches; ratio of alternating stress to mean stress; subscript "axial"; A basis for mechanical-property values (see Section 1.4.1.1)
AISI	American Iron and Steel Institute
AMS	Aerospace Materials Specification (published by Society of Automotive Engineers, Inc.)
AN	Air Force-Navy Aeronautical Standard
Ann	Annealed
ASTM	American Society for Testing and Materials
a	Amplitude; crack or flaw dimension
a_c	Critical half crack length
a_o	Initial half crack length
B	Biaxial ratio (see Equation 1.3.2.8); B basis for mechanical-property values (see Section 1.4.1.1)
Btu	British thermal unit(s)
BUS	Individual or typical bearing ultimate strength
BYS	Individual or typical bearing yield strength
b	Width of sections; subscript "bending"
br	Subscript "bearing"
C	Specific heat; Celsius; Constant
CEM	Consumable electrode melted
CRES	Corrosion resistant steel (stainless steel)
C(T)	Compact tension
CYS	Individual or typical compressive yield strength
c	Fixity coefficient for columns; subscript "compression"
cpm	Cycles per minute
D	Diameter; hole or fastener diameter; dimpled hole
d	Mathematical operator denoting differential

CHAPTER 2

STEEL

This chapter contains the engineering properties and related characteristics of steels used in aircraft and missile structural applications. General comments on engineering properties and other considerations related to alloy selection are presented in Section 2.1. Mechanical and physical property data and characteristics pertinent to specific steel groups or individual steels are reported in Sections 2.2 through 2.7. Element properties are presented in Section 2.8.

2.1 GENERAL

The selection of the proper grade of steel for a specific application is based on material properties and on manufacturing, environmental, and economic considerations. Some of these considerations are outlined in the sections that follow.

2.1.1 ALLOY INDEX — The steel alloys listed in this chapter are arranged in major sections that identify broad classifications of steel partly associated with major alloying elements, partly associated with processing, and consistent generally with steel-making technology. Specific alloys are identified as shown in Table 2.1.1.

Table 2.1.1. Steel Alloy Index

Section	Alloy Designation
2.2	**Carbon steels**
2.2.1	AISI 1025
2.3	**Low-alloy steels (AISI and proprietary grades)**
2.3.1	Specific alloys
2.4	**Intermediate alloy steels**
2.4.1	5Cr-Mo-V
2.4.2	9Ni-4Co-0.20C
2.4.3	9Ni-4Co-0.30C
2.5	**High alloy steels**
2.5.1	18 Ni maraging steels
2.5.2	AF1410
2.5.3	AerMet 100
2.6	**Precipitation and transformation hardening steel (stainless)**
2.6.1	AM-350
2.6.2	AM-355
2.6.3	Custom 450
2.6.4	Custom 455
2.6.5	PH13-8Mo
2.6.6	15-5PH
2.6.7	PH15-7Mo
2.6.8	17-4PH
2.6.9	17-7PH
2.7	**Austenitic stainless steels**
2.7.1	AISI Type 301

2.1.2 MATERIAL PROPERTIES — One of the major factors contributing to the general utility of steels is the wide range of mechanical properties which can be obtained by heat treatment. For example, softness and good ductility may be required during fabrication of a part and very high strength during its service life. Both sets of properties are obtainable in the same material.

All steels can be softened to a greater or lesser degree by annealing, depending on the chemical composition of the specific steel. Annealing is achieved by heating the steel to an appropriate temperature, holding, then cooling it at the proper rate.

Likewise, steels can be hardened or strengthened by means of cold working, heat treating, or a combination of these.

Cold working is the method used to strengthen both the low-carbon unalloyed steels and the highly alloyed austenitic stainless steels. Only moderately high strength levels can be attained in the former, but the latter can be cold rolled to quite high strength levels, or "tempers". These are commonly supplied to specified minimum strength levels.

Heat treating is the principal method for strengthening the remainder of the steels (the low-carbon steels and the austenitic steels cannot be strengthened by heat treatment). The heat treatment of steel may be of three types: martensitic hardening, age hardening, and austempering. Carbon and alloy steels are martensitic-hardened by heating to a high temperature, or "austenitizing", and cooling at a recommended rate, often by quenching in oil or water. This is followed by "tempering", which consists of reheating to an intermediate temperature to relieve internal stresses and to improve toughness.

The maximum hardness of carbon and alloy steels, quenched rapidly to avoid the nose of the isothermal transformation curve, is a function in general of the alloy content, particularly the carbon content. Both the maximum thickness for complete hardening or the depth to which an alloy will harden under specific cooling conditions, and the distribution of hardness can be used as a measure of a material's hardenability.

A relatively new class of steels is strengthened by age hardening. This heat treatment is designed to dissolve certain constituents in the steel, then precipitate them in some preferred particle size and distribution. Since both the martensitic hardening and the age-hardening treatments are relatively complex, specific details are presented for individual steels elsewhere in this chapter.

Recently, special combinations of working and heat treating have been employed to further enhance the mechanical properties of certain steels. At the present time, the use of these specialized treatments is not widespread.

Another method of heat treatment for steels is austempering. In this process, ferrous steels are austenitized, quenched rapidly to avoid transformation of the austenite to a temperature below the pearlite and above the martensite formation ranges, allowed to transform isothermally at that temperature to a completely bainitic structure, and finally cooled to room temperature. The purpose of austempering is to obtain increased ductility or notch toughness at high hardness levels, or to decrease the likelihood of cracking and distortion that might occur in conventional quenching and tempering.

2.1.2.1 *Mechanical Properties* —

2.1.2.1.1 *Strength (Tension, Compression, Shear, Bearing)* — The strength properties presented are those used in structural design. The room-temperature properties are shown in tables following the comments for individual steels. The variations in strength properties with temperature are presented graphically as percentages of the corresponding room-temperature strength property, also described in Section 9.3.1 and associated subsections. These strength properties may be reduced appreciably by prolonged exposure at elevated temperatures.

The strength of steels is temperature-dependent, decreasing with increasing temperature. In addition, steels are strain rate-sensitive above about 600 to 800°F, particularly at temperatures at which creep occurs. At lower strain rates, both yield and ultimate strengths decrease.

The modulus of elasticity is also temperature-dependent and, when measured by the slope of the stress-strain curve, it appears to be strain rate-sensitive at elevated temperatures because of creep during loading. However, on loading or unloading at high rates of strain, the modulus approaches the value measured by dynamic techniques.

Steel bars, billets, forgings, and thick plates, especially when heat treated to high strength levels, exhibit variations in mechanical properties with location and direction. In particular, elongation, reduction of area, toughness, and notched strength are likely to be lower in either of the transverse directions than in the longitudinal direction. This lower ductility and/or toughness results both from the fibering caused by the metal flow and from nonmetallic inclusions which tend to be aligned with the direction of primary flow. Such anisotropy is independent of the depth-of-hardening considerations discussed elsewhere. It can be minimized by careful control of melting practices (including degassing and vacuum-arc remelting) and of hot-working practices. In applications where transverse properties are critical, requirements should be discussed with the steel supplier and properties in critical locations should be substantiated by appropriate testing.

2.1.2.1.2 *Elongation* — The elongation values presented in this chapter apply in both the longitudinal and long transverse directions, unless otherwise noted. Elongation in the short transverse (thickness) direction may be lower than the values shown.

2.1.2.1.3 *Fracture Toughness* — Steels (as well as certain other metals), when processed to obtain high strength, or when tempered or aged within certain critical temperature ranges, may become more sensitive to the presence of small flaws. Thus, as discussed in Section 1.4.12, the usefulness of high-strength steels for certain applications is largely dependent on their toughness. It is generally noted that the fracture toughness of a given alloy product decreases relative to increase in the yield strength. The designer is cautioned that the propensity for brittle fracture must be considered in the application of high-strength alloys for the purpose of increased structural efficiency.

Minimum, average, and maximum values, as well as coefficient of variation of plane-strain fracture toughness for several steel alloys, are presented in Table 2.1.2.1.3. These values are presented as indicative information and do not have the statistical reliability of room-temperature mechanical properties. Data showing the effect of temperature are presented in the respective alloy sections where the information is available.

2.1.2.1.4 *Stress-Strain Relationships* — The stress-strain relationships presented in this chapter are prepared as described in Section 9.3.2.

2.1.2.1.5 *Fatigue* — Axial-load fatigue data on unnotched and notched specimens of various steels at room temperature and at other temperatures are shown as S/N curves in the appropriate section. Surface finish, surface finishing procedures, metallurgical effects from heat treatment, environment and other factors influence fatigue behavior. Specific details on these conditions are presented as correlative information for the S/N curve.

Table 2.1.2.1.3. Values of Room Temperature Plane-Strain Fracture Toughness of Steel Alloys[a]

Alloy	Heat Treat Condition	Product Form	Orientation[b]	Yield Strength Range, ksi	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi $\sqrt{in.}$			
									Max.	Avg.	Min.	Coefficient of Variation
D6AC	1650°F, Aus-Bay Quench 975°F, SQ 375°F, 1000°F 2 + 2	Plate	L-T	217	1.5	1	19	0.6	88	62	40	22.5
D6AC	1650°F, Aus-Bay Quench 975°F, SQ 400°F, 1000°F 2 + 2	Plate	L-T	217	0.8	1	103	0.6-0.8	92	64	44	18.9
D6AC	1650°F, Aus-Bay Quench 975°F, SQ 400°F, 1000°F 2 + 2	Forging	L-T	214	0.8-1.5	1	53	0.6-0.8	96	66	39	18.6
D6AC	1700°F, Aus-Bay Quench 975°F, OQ 140°F, 1000°F 2 + 2	Plate	L-T	217	0.8-1.5	1	30	0.6-0.8	101	92	64	8.9
D6AC	1700°F, Aus-Bay Quench 975°F, OQ 140°F, 1000°F 2 + 2	Forging	L-T	214	0.8-1.5	1	34	0.7	109	95	81	6.7
9Ni-4Co-.20C	Quench and Temper	Hand Forging	L-T	185-192	3.0	2	27	1.0-2.0	147	129	107	8.3
9Ni-4Co-.20C	1650°F, 1-2 Hr, AC, 1525°F, 1-2 Hr, OQ, -100°F, Temp	Forging	L-T	186-192	3.0-4.0	3	17	1.5-2.0	147	134	120	8.5
PH13-8Mo	H1000	Forging	L-T	205-212	4.0-8.0	3	12	0.7-2.0	104	90	49	21.5

a These values are for information only.
b Refer to Figure 1.4.12.3 for definition of symbols.

2.1.2.2 *Physical Properties* — The physical properties (ω, C, K, and α) of steels may be considered to apply to all forms and heat treatments unless otherwise indicated.

2.1.3 ENVIRONMENTAL CONSIDERATIONS — The effects of exposure to environments such as stress, temperature, atmosphere, and corrosive media are reported for various steels. Fracture toughness of high-strength steels and the growth of cracks by fatigue may be detrimentally influenced by humid air and by the presence of water or saline solutions. Some alleviation may be achieved by heat treatment and all high-strength steels are not similarly affected.

In general, these comments apply to steels in their usual finished surface condition, without surface protection. It should be noted that there are available a number of heat-resistant paints, platings, and other surface coatings that are employed either to improve oxidation resistance at elevated temperature or to afford protection against corrosion by specific media. In employing electrolytic platings, special consideration should be given to the removal of hydrogen by suitable baking. Failure to do so may result in lowered fracture toughness or embrittlement.

CHAPTER 3

ALUMINUM

3.1 GENERAL

This chapter contains the engineering properties and related characteristics of wrought and cast aluminum alloys used in aircraft and missile structural applications.

General comments on engineering properties and the considerations relating to alloy selection are presented in Section 3.1. Mechanical and physical property data and characteristics pertinent to specific alloy groups or individual alloys are reported in Sections 3.2 through 3.10. Element properties are presented in Section 3.11.

Aluminum is a lightweight, corrosion-resistant structural material that can be strengthened through alloying and, dependent upon composition, further strengthened by heat treatment and/or cold working [Reference 3.1(a)]. Among its advantages for specific applications are: low density, high strength-to-weight ratio, good corrosion resistance, ease of fabrication and diversity of form.

Wrought and cast aluminum and aluminum alloys are identified by a four-digit numerical designation, the first digit of which indicates the alloy group as shown in Table 3.1. For structural wrought aluminum alloys the last two digits identify the aluminum alloy. The second digit indicates modifications of the original alloy or impurity limits. For cast aluminum and aluminum alloys the second and third digits identify the aluminum alloy or indicate the minimum aluminum percentage. The last digit, which is to the right of the decimal point, indicates the product form: XXX.0 indicates castings, and XXX.1 and XXX.2 indicate ingot.

Table 3.1. Basic Designation for Wrought and Cast Aluminum Alloys [Reference 3.1(b)]

Alloy Group	Major Alloying Elements	Alloy Group	Major Alloying Groups
	Wrought Alloys		Cast Alloys
1XXX	99.00 percent minimum aluminum	1XX.0	99.00 percent minimum aluminum
2XXX	Copper	2XX.0	Copper
3XXX	Manganese	3XX.0	Silicon with added copper and/or magnesium
4XXX	Silicon	4XX.0	Silicon
5XXX	Magnesium	5XX.0	Magnesium
6XXX	Magnesium and Silicon	6XX.0	Unused Series
7XXX	Zinc	7XX.0	Zinc
8XXX	Other Elements	8XX.0	Tin
9XXX	Unused Series	9XX.0	Other Elements

Table 3.1.1. Aluminum Alloy Index

Section	Alloy Designation	Section	Alloy Designation
3.2	2000 series wrought alloys	3.6.3	6151
3.2.1	2014	3.7	7000 series wrought alloys
3.2.2	2107	3.7.1	7010
3.2.3	2024	3.7.2	7049/7149
3.2.4	2025	3.7.3	7050
3.2.5	2090	3.7.4	7075
3.2.6	2124	3.7.5	7150
3.2.7	2219	3.7.6	7175
3.2.8	2519	3.7.7	7249
3.2.9	2618	3.7.8	7475
3.3	3000 series wrought alloys	3.8	200.0 series cast alloys
3.4	4000 series wrought alloys	3.8.1	A201.0
3.5	5000 series wrought alloys	3.9	300.0 series cast alloys
3.5.1	5052	3.9.1	354.0
3.5.2	5083	3.9.2	355.0
3.5.3	5086	3.9.3	C355.0
3.5.4	5454	3.9.4	356.0
3.5.5	5456	3.9.5	A356.0
3.6	6000 series wrought alloys	3.9.6	A357.0
3.6.1	6013	3.9.7	D357.0
3.6.2	6061	3.9.8	359.0

3.1.1 ALUMINUM ALLOY INDEX — The layout of this chapter is in accordance with this four-digit number system for both wrought and cast alloys [Reference 3.1(b)]. Table 3.1.1 is the aluminum alloy index that illustrates both the general section layout as well as details of those specific aluminum alloys presently contained in this chapter. The wrought alloys are in Sections 3.2 through 3.7; whereas the cast alloys are in Sections 3.8 and 3.9.

3.1.2 MATERIAL PROPERTIES — The properties of the aluminum alloys are determined by the alloy content and method of fabrication. Some alloys are strengthened principally by cold work, while others are strengthened principally by solution heat treatment and precipitation hardening [Reference 3.1(a)]. The temper designations, shown in Table 3.1.2 (which is based on Reference 3.1.2), are indicative of the type of strengthening mechanism employed.

Among the properties presented herein, some, such as the room-temperature, tensile, compressive, shear and bearing properties, are either specified minimum properties or derived minimum properties related directly to the specified minimum properties. They may be directly useful in design. Data on the effect of temperature on properties are presented so that percentages may be applied directly to the room-temperature minimum properties. Other properties, such as the stress-strain curve, fatigue and fracture toughness data, and modulus of elasticity values, are presented as average or typical values, which may be used in assessing the usefulness of the material for certain applications. Comments on the effect of temperature on properties are given in Sections 3.1.2.1.7 and 3.1.2.1.8; comments on the corrosion resistance are given in Section 3.1.2.3; and comments on the effects of manufacturing practices on these properties are given in Section 3.1.3.

Table 3.1.2. Temper Designation System for Aluminum Alloys

Temper Designation System[ab]

The temper designation system is used for all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

Basic Temper Designations

F **as fabricated**. Applies to the products of shaping processes in which no special control over thermal conditions or strain-hardening is employed. For wrought products, there are no mechanical property limits.

O **annealed**. Applies to wrought products which are annealed to obtain the lowest strength temper, and to cast products which are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.

H **strain-hardened (wrought products only)**. Applies to products which have their strength increased by strain-hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W **solution heat-treated**. An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated: for example, W ½ hr.

T **thermally treated to produce stable tempers other than F, O, or H**. Applies to products which are thermally treated, with or without supplementary strain-hardening, to produce stable tempers. The T is always followed by one or more digits.

Subdivisions of H Temper: Strain-hardened.

The first digit following H indicates the specific combination of basic operations, as follows:

H1 **strain-hardened only**. Applies to products which are strain-hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

H2 **strain-hardened and partially annealed**. Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H1 tempers and slightly higher elongation. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

H3 **strain-hardened and stabilized**. Applies to products which are strain-hardened and whose mechanical properties are stabilized either by a low temperature thermal treatment or as a result

a From reference 3.1.2.

b Temper designations conforming to this standard for wrought aluminum and wrought aluminum alloys, and aluminum alloy castings may be registered with the Aluminum Association provided: (1) the temper is used or is available for use by more than one user, (2) mechanical property limits are registered, (3) characteristics of the temper are significantly different from those of all other tempers which have the same sequence of basic treatments and for which designations already have been assigned for the same alloy and product, and (4) the following are also registered if characteristics other than mechanical properties are considered significant: (a) test methods and limits for the characteristics or (b) the specific practices used to produce the temper.

Table 3.1.2. Temper Designation System for Aluminum Alloys — Continued

of heat introduced during fabrication. Stabilization usually improves ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age-soften at room temperature. The number following this designation indicates the degree of strain-hardening remaining after the stabilization treatment.

The digit following the designations H1, H2, and H3 indicates the degree of strain hardening. Numeral 8 has been assigned to indicate tempers having an ultimate tensile strength equivalent to that achieved by a cold reduction (temperature during reduction not to exceed 120°F) of approximately 75 percent following a full anneal. Tempers between O (annealed) and 8 are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between that of the O temper and that of the 8 temper is designated by the numeral 4; about midway between the O and 4 tempers by the numeral 2; and about midway between 4 and 8 tempers by the numeral 6. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper by 2.0 ksi or more. For two-digit H tempers whose second digit is odd, the standard limits for ultimate tensile strength are exactly midway between those of the adjacent two digit H tempers whose second digits are even.

NOTE: For alloys which cannot be cold reduced an amount sufficient to establish an ultimate tensile strength applicable to the 8 temper (75 percent cold reduction after full anneal), the 6 temper tensile strength may be established by a cold reduction of approximately 55 percent following a full anneal, or the 4 temper tensile strength may be established by a cold reduction of approximately 35 percent after a full anneal.

The third digit[c], when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties or both differ from, but are close to, that (or those) for the two-digit H temper designation to which it is added, or when some other characteristic is significantly affected.

NOTE: The minimum ultimate tensile strength of a three-digit H temper must be at least as close to that of the corresponding two-digit H temper as it is to the adjacent two-digit H tempers. Products of the H temper whose mechanical properties are below H_1 shall be variations of H_1.

Three-digit H Tempers

H_11 Applies to products which incur sufficient strain hardening after the final anneal that they fail to qualify as annealed but not so much or so consistent an amount of strain hardening that they qualify as H_1.

H112 Applies to products which may acquire some temper from working at an elevated temperature and for which there are mechanical property limits.

**Subdivisions of T Temper:
Thermally Treated**

Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows.[d]

T1 **cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition**. Applies to products which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T2 **cooled from an elevated temperature shaping process, cold worked and naturally aged to a substantially stable condition**. Applies to products which are cold worked to improve strength after cooling from an elevated temperature shaping process, or in which the effect of

c Numerals 1 through 9 may be arbitrarily assigned as the third digit and registered with The Aluminum Association for an alloy and product to indicate a variation of a two-digit H temper (see footnote b).

d A period of natural aging at room temperature may occur between or after the operations listed for the T tempers. Control of this period is exercised when it is metallurgically important.

Table 3.1.2. Temper Designation System for Aluminum Alloys — Continued

cold work in flattening or straightening is recognized in mechanical property limits.

T3 solution heat-treated[e], cold worked, and naturally aged to a substantially stable condition. Applies to products which are cold worked to improve strength after solution heat-treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T4 solution heat-treated[e] and naturally aged to a substantially stable condition. Applies to products which are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T5 cooled from an elevated temperature shaping process and artificially aged. Applies to products which are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T6 solution heat-treated[e] and artificially aged. Applies to products which are not cold worked after solution heat-treatment or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7 solution heat-treated[e] and overaged/stabilized. Applies to wrought products that are artificially aged after solution heat-treatment to carry them beyond a point of maximum strength to provide control of some significant characteristic. Applies to cast products that are artificially aged after solution heat-treatment to provide dimensional and strength stability.

T8 solution heat-treated[e], cold worked, and artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9 solution heat-treated[e], artificially aged, and cold worked. Applies to products which are cold worked to improve strength.

T10 cooled from an elevated temperature shaping process, cold worked, and artificially aged. Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

Additional digits[f], the first of which shall not be zero, may be added to designations T1 through T10 to indicate a variation in treatment which significantly alters the product characteristics[g] that are or would be obtained using the basic treatment.

The following specific additional digits have been assigned for stress-relieved tempers of wrought products:

Stress Relieved by Stretching

T_51 Applies to plate and rolled or cold-finished rod and bar when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. The products receive no further straightening after stretching.

e Solution heat treatment is achieved by heating cast or wrought products to a suitable temperature, holding at that temperature long enough to allow constituents to enter into solid solution and cooling rapidly enough to hold the constituents in solution. Some 6000 series alloys attain the same specified mechanical properties whether furnace solution heat-treated or cooled from an elevated temperature shaping process at a rate rapid enough to hold constituents in solution. In such cases the temper designations T3, T4, T6, T7, T8, and T9 are used to apply to either process and are appropriate designations.

f Additional digits may be arbitrarily assigned and registered with the Aluminum Association for an alloy and product to indicate a variation of tempers T1 through T10 even though the temper representing the basic treatment has not been registered (see footnote b). Variations in treatment which do not alter the characteristics of the product are considered alternate treatments for which additional digits are not assigned.

g For this purpose, characteristic is something other than mechanical properties. The test method and limit used to evaluate material for this characteristic are specified at the time of the temper registration.

Table 3.1.2. Temper Designation System for Aluminum Alloys — Continued

Plate .... 1½ to 3% permanent set.
Rolled or Cold-Finished
Rod and Bar .... 1 to 3% permanent set.
Die or Ring Forgings
and Rolled Rings .... 1 to 5% permanent set.

T_510 Applies to extruded rod, bar, shapes and tube and to drawn tube when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. These products receive no further straightening after stretching.

Extruded Rod, Bar, Shapes
and Tube .... 1 to 3% permanent set.
Drawn Tube .... ½ to 3% permanent set.

T_511 Applies to extruded rod, bar, shapes and tube and to drawn tube when stretched the indicated amounts after solution heat-treatment or after cooling from an elevated temperature shaping process. These products may receive minor straightening after stretching to comply with standard tolerances.

Stress Relieved by Compressing

T_52 Applies to products which are stress-relieved by compressing after solution heat-treatment or cooling from an elevated temperature shaping process to produce a set of 1 to 3 percent.

Stress Relieved by Combined Stretching and Compressing

T_54 Applies to die forgings which are stress relieved by restriking cold in the finish die.

NOTE: The same digits (51, 52, 54) may be added to the designation W to indicate unstable solution heat-treated and stress-relieved treatment.

The following temper designations have been assigned for wrought product test material heat-treated from annealed (O, O1, etc.) or F temper.[h]

T42 Solution heat-treated from annealed or F temper and naturally aged to a substantially stable condition.

T62 Solution heat-treated from annealed or F temper and artificially aged.

Temper designations T42 and T62 may also be applied to wrought products heat-treated from any temper by the user when such heat-treatment results in the mechanical properties applicable to these tempers.

Variations of O Temper: Annealed

A digit following the O, when used, indicates a product in the annealed condition have special characteristics. NOTE: As the O temper is not part of the strain-hardened (H) series, variations of O temper shall not apply to products which are strain-hardened after annealing and in which the effect of strain-hardening is recognized in the mechanical properties or other characteristics.

Assigned O Temper Variations

The following temper designation has been assigned for wrought products high temperature annealed to accentuate ultrasonic response and provide dimensional stability.

O1 Thermally treated at approximately same time and temperature required for solution heat treatment and slow cooled to room temperature. Applicable to products which are to be machined prior to solution heat treatment by the user. Mechanical Property limits are not applicable.

Designation of Unregistered Tempers

The letter P has been assigned to denote H, T and O temper variations that are negotiated between manufacturer and purchaser. The letter P immediately follows the temper designation that

h When the user requires capability demonstrations from T-temper, the seller shall note “capability compliance” adjacent to the specified ending tempers. Some examples are: “-T4 to -T6 Capability Compliance as for aging” or “-T351 to -T4 Capability Compliance as for resolution heat treating.”

Table 3.1.2. Temper Designation System for Aluminum Alloys — Continued

most nearly pertains. Specific examples where such designation may be applied include the following:

The use of the temper is sufficiently limited so as to preclude its registration. (Negotiated H temper variations were formerly indicated by the third digit zero.)

The test conditions (sampling location, number of samples, test specimen configuration, etc.) are different from those required for registration with the Aluminum Association.

The mechanical property limits are not established on the same basis as required for registration with the Aluminum Association.

It should be recognized not all combinations of stress and environment have been investigated, and it may be necessary to evaluate an alloy under the specific conditions involved for certain critical applications.

3.1.2.1 *Mechanical Properties* —

3.1.2.1.1 *Strength (Tension, Compression, Shear, Bearing)* — The design strength properties at room temperature are listed at the beginning of the section covering the properties of an alloy. The effect of temperature on these properties is indicated in figures which follow the tables.

The A- and B-basis values for tensile properties for the direction associated with the specification requirements are based upon a statistical analysis of production quality control data obtained from specimens tested in accordance with procurement specification requirements. For sheet and plate of heat-treatable alloys, the specified minimum values are for the long-transverse (LT) direction, while for sheet and plate of nonheat treatable alloys and for rolled, drawn, or extruded products, the specified minimum values are for the longitudinal (L) direction. For forgings, the specified minimum values are stated for at least two directions. The design tensile properties in other directions and the compression, shear, and bearing properties are "derived" properties, based upon the relationships among the properties developed by tests of at least ten lots of material and applied to the appropriate established A, B, or S properties. All of these properties are representative of the regions from which production quality control specimens are taken, but may not be representative of the entire cross section of products appreciably thicker than the test specimen or products of complex cross sections.

Tensile and compressive strengths are given for the longitudinal, long-transverse, and short-transverse directions wherever data are available. Short-transverse strengths may be relatively low, and transverse properties should not be assumed to apply to the short-transverse direction unless so stated. In those instances where the direction in which the material will be used is not known, the lesser of the applicable longitudinal or transverse properties should be used.

Bearing strengths are given without reference to direction and may be assumed to be about the same in all directions, with the exception of plate, die forging, and hand forging. A reduction factor is used for edgewise bearing load in thick bare and clad plate of 2000 and 7000 series alloys. The results of bearing tests on longitudinal and long-transverse specimens taken edgewise from plate, die forging, and hand forging have shown that the edgewise bearing strengths are substantially lower than those of specimens taken parallel to the surface. The bearing specimen orientations in thick plate are shown in Figure 3.1.2.1.1(a). For plate, bearing specimens are oriented so that the width of the specimen is parallel to the surfaces of the plate (flatwise); consequently, in cases where the stress condition approximates that of the longitudinal or long-transverse edgewise orientations, the reductions in design values shown in Table 3.1.2.1.1 should be made.

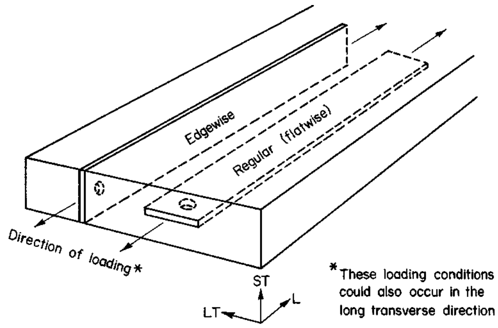

Figure 3.1.2.1.1(a). Bearing specimen orientation in thick plate.

Table 3.1.2.1.1. Bearing Property Reductions for Thick Plate of 2000 and 7000 Series Alloys

	Bearing Property Reduction, percent
Thickness (in.) ...	1.001-6.000
F_{bru} (e/D = 1.5)	15
F_{bru} (e/D = 2.0)	10
F_{bry} (e/D = 1.5)	5
F_{bry} (e.D = 2.0)	5

It should be noted that in recent years, bearing data have been presented from tests made in accordance with ASTM E 238 which requires clean pins and specimens. See Reference 3.1.2.1.1 for additional information. Designers should consider a reduction factor in applying these values to structural analyses.

For die and hand forgings, bearing specimens are taken edgewise so that no reduction factor is necessary. In the case of die forgings, the location of bearing specimens is shown in Figures 3.1.2.1.1(b) and (c). For die forgings with cross-sectional shapes in the form of an I-beam or a channel, longitudinal bearing specimens are oriented so the width of the specimens is normal to the parting plane (edgewise). The specimens are positioned so the bearing test holes are midway between the parting plane and the top of the flange. The severity of metal flow at the parting plane near the flash can be expected to vary considerably for web-flange type die forgings; therefore, for consistency, the bearing test hole should not be located on the parting plane. However, in the case of large, bulky-type die forgings, with a cross-sectional shape similar to a square, rectangle, or trapezoid, as shown in Figure 3.1.2.1.1(c), longitudinal bearing specimens are oriented edgewise to the parting plane, but the specimens are positioned so the bearing test holes are located on the parting plane. Similarly, for hand forgings, bearing specimens are oriented edgewise and the specimens are positioned at the ½ thickness location.

Shear strengths also vary to some extent with plane of shear and direction of loading but the differences are not so consistent [Reference 3.1.2.1.1(c)]. The standard test method for the determination of shear strength of aluminum alloy products, 3/16 inch and greater in thickness, is contained in ASTM B 769.

Shear strength values are presented without reference to grain direction, except for hand forgings. For products other than hand forgings, the lowest shear strength exhibited by tests in the various grain

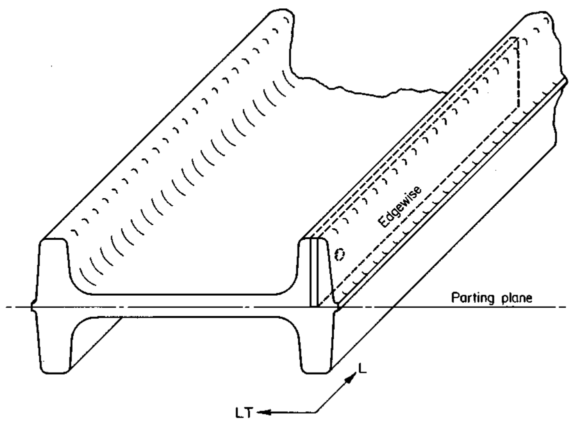

Figure 3.1.2.1.1(b). Bearing specimen orientation for web-flange type die forging.

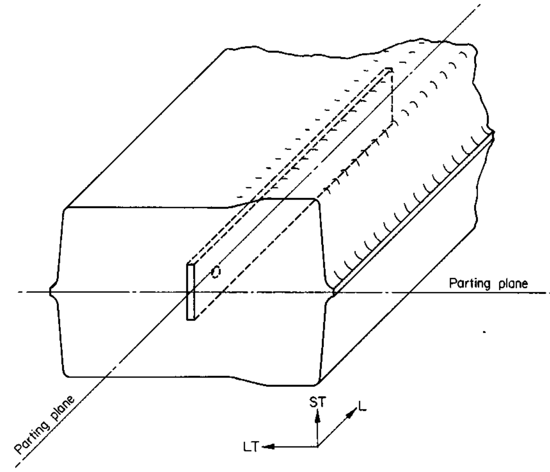

Figure 3.1.2.1.1(c). Bearing specimen orientation for thick cross-section die forging.

directions is the design value. For hand forgings, the shear strength in short-transverse direction may be significantly lower than for the other two grain directions. Consequently, the shear strength for hand forgings is presented for each grain direction.

For clad sheet and plate (i.e., containing thin surface layers of material of a different composition for added corrosion protection), the strength values are representative of the composite (i.e., the cladding and the core). For sheet and thin plate (≤0.499 inch), the quality-control test specimens are of the full thickness, so that the guaranteed tensile properties and the associated derived values for these products directly represent the composite. For plate ≥0.500 inch in thickness, the quality-control test specimens are machined from the core so the guaranteed tensile properties in specifications reflect the core material only, not the composite. Therefore, the design tensile properties for the thicker material are obtained by adjustment of the specification tensile properties and the other related properties to represent the composite, using the nominal total cladding thickness and the typical tensile properties of the cladding material.

For clad aluminum sheet and plate products, it is also important to distinguish between primary and secondary modulus values. The initial, or primary, modulus represents an average of the elastic moduli of the core and cladding; it applies only up to the proportional limit of the cladding. For example, the primary modulus of 2024-T3 clad sheet applies only up to about 6 ksi. Similarly, the primary modulus of 7075-T6 clad sheet applies only up to approximately 12 ksi. A typical use of primary moduli is for low amplitude, high frequency fatigue.

3.1.2.1.2 *Elongation* — Elongation values are included in the tables of room-temperature mechanical properties. In some cases where the elongation is a function of material thickness, a supplemental table is provided. Short-transverse elongations may be relatively low, and long-transverse values should not be assumed to apply to the short-transverse direction.

3.1.2.1.3 *Stress-Strain Relationship* — The stress-strain relationships presented, which include elastic and compressive tangent moduli, are typical curves based on three or more lots of test data. Being typical, these curves will not correspond to yield strength data presented as design allowables (minimum values). However, the stress-strain relationships are no less useful, since there are well-known methods for using these curves in design by reducing them to a minimum curve affine to the typical curve or by using Ramberg-Osgood parameters obtained from the typical curves.

3.1.2.1.4 *Creep and Stress Rupture* — Sustained stressing at elevated temperature sufficient to result in appreciable amounts of creep deformation (e.g., more than 0.2 percent) may result in decreased strength and ductility. It may be necessary to evaluate an alloy under its stress-temperature environment for critical applications where sustained loading is anticipated (see Reference 3.1.2.1.4).

3.1.2.1.5 *Fatigue* — Fatigue S/N curves are presented for those alloys for which sufficient data are available. Data for both smooth and notched specimens are presented. The data from which the curves were developed were insufficient to establish scatter bands and do not have the statistical reliability of the room-temperature mechanical properties; the values should be considered to be representative for the respective alloys.

The fatigue strengths of aluminum alloys, with both notched and unnotched specimens, are at least as high or higher at subzero temperatures than at room temperature [References 3.1.2.1.5(a) through (c)]. At elevated temperatures, the fatigue strengths are somewhat lower than at room temperature, the difference increasing with increase in temperature.

The data presented do not apply directly to the design of structures because they do not take into account the effect of stress raisers such as reentrant corners, notches, holes, joints, rough surfaces, and other similar conditions which are present in fabricated parts. The localized high stresses induced in fabricated parts by such stress raisers are of much greater importance for repeated loading than they are for static loading and may reduce the fatigue life of fabricated parts far below that which would be predicted by comparing the smooth-specimen fatigue strength directly with the nominal calculated stresses for the parts in question. See References 3.1.2.1.5 (d) through (q) for information on how to use high-strength aluminum alloys, Reference 3.1.2.1.5(r) for details on the static and fatigue strengths of high-strength aluminum-alloy bolted joints, Reference 3.1.2.1.5(s) for single-rivet fatigue-test data, and Reference 1.4.9.3(b) for a general discussion of designing for fatigue. Fatigue-crack-growth data are presented in the various alloy sections.

3.1.2.1.6 *Fracture Toughness* — Typical values of plane-strain fracture toughness, K_{Ic}, [Reference 3.1.2.1.6(a)] for the high-strength aluminum alloy products are presented in Table 3.1.2.1.6. Minimum, average, and maximum values as well as coefficient of variation are presented for the alloys and tempers for which valid data are available [References 3.1.2.1.6(b) through (j)]. Although representative, these values do not have the statistical reliability of the room-temperature mechanical properties.

Graphic displays of the residual strength behavior of center-cracked tension panels are presented in the various alloy sections. The points denote the experimental data from which the curve of fracture toughness was derived.

3.1.2.1.7 *Cryogenic Temperatures* — In general, the strengths (including fatigue strengths) of aluminum alloys increase with decrease in temperature below room temperature [References 3.1.2.1.7(a) and (b)]. The increase is greatest over the range from about -100 to -423°F (liquid hydrogen temperature); the strengths at -452°F (liquid helium temperature) are nearly the same as at -423°F [References 3.1.2.1.7(c) and (d)]. For most alloys, elongation and various indices of toughness remain nearly constant or increase with decrease in temperature, while for the 7000 series, modest reductions are observed [References 3.1.2.1.7(d) and (e)]. None of the alloys exhibit a marked transition in fracture resistance over a narrow range of temperature indicative of embrittlement.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]

Alloy/Temper	Product Form	Orien-tation[b]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi $\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
2014-T651	Plate	L-T	≥0.5	1	24	0.5-1.0	25	22	19	8.4	
2014-T651	Plate	T-L	≥0.5	2	34	0.5-1.0	23	21	18	6.5	
2014-T652	Hand Forging	L-T	≥0.5	2	15	0.8-2.0	48	31	24	21.8	
2014-T652	Hand Forging	T-L	≥0.8	2	15	0.8-2.0	30	21	18	14.4	
2024-T351	Plate	L-T	≥1.0	2	11	0.8-2.0	43	31	27	16.5	
2024-T851	Plate	L-S	1.4-3.0	4	11	0.5-0.8	32	25	20	17.8	
2024-T851	Plate	L-T	≥0.5	11	102	0.4-1.4	32	23	15	10.1	
2024-T851	Plate	T-L	0.4-4.0	9	80	0.4-1.4	25	20	18	8.8	
2024-T852	Forging	T-L	2.0-7.0	3	20	0.7-2.0	25	19	15	15.5	
2024-T852	Hand Forging	L-T	----	4	35	0.8-2.0	38	28	19	18.4	
2024-T852	Hand Forging	T-L	----	2	17	0.7-2.0	22	18	14	14.4	
2124-T851	Plate	L-T	≥0.8	13	497	0.5-2.5	38	29	18	10.4	24
2124-T851	Plate	T-L	0.6-6.0	10	509	0.5-2.0	32	25	19	9.7	20
2124-T851	Plate	S-L	≥0.5	6	489	0.3-1.5	27	21	16	9.8	18
2219-T851	Plate	L-T	----	4	67	1.0-2.5	38	33	30	7.2	
2219-T851	Plate	T-L	≥1.0	6	108	0.8-2.5	37	29	20	10.1	
2219-T851	Plate	S-L	≥0.8	3	24	0.5-1.5	26	22	20	9.6	
2219-T851	Forging	S-L	----	1	85	1.0-1.5	34	25	19	12.1	
2219-T8511	Extrusion	T-L	----	1	19	1.8-2.0	34	29	23	12.3	
2219-T852	Forging	S-L	----	2	60	0.8-2.0	35	25	20	12.1	
2219-T852	Hand Forging	L-T	----	2	32	1.5-2.5	46	38	30	9.7	
2219-T852	Hand Forging	T-L	≥1.5	2	28	1.5-2.5	30	27	22	8.4	
2219-T87	Plate	L-T	≥1.5	3	11	0.8-2.0	34	27	25	9.3	
2219-T87	Plate	T-L	----	1	11	1.0	22	22	19	3.9	
7049-T73	Die Forging	L-T	1.4	3	21	0.5-1.0	34	30	27	7.4	
7049-T73	Die Forging	S-L	≥0.5	3	46	0.5-1.0	26	22	18	9.7	
7049-T73	Hand Forging	L-T	≥0.5	2	28	0.5-1.0	37	30	23	12.1	
7049-T73	Hand Forging	T-L	2.0-7.1	2	27	1.0	28	22	18	12.5	
7049-T73	Hand Forging	S-L	1.0	2	24	0.8-1.0	22	19	14	14.2	
7050-T7351	Plate	L-T	1.0-6.0	2	31	1.0-2.0	43	35	28	11.3	
7050-T7351	Plate	T-L	2.0-6.0	1	29	1.5-2.0	35	30	25	8.5	
7050-T7351	Plate	S-L	2.0-6.0	1	30	0.8-1.5	30	28	25	4.6	
7050-T74	Die Forging	S-L	0.6-7.1	3	12	0.6-2.0	27	24	21	8.8	

a These values are for information only.
b Refer to Figure 1.4.12.3 for definition of symbols.
c Varies with thickness.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]—Continued

Alloy/Temper	Product Form	Orientation[b]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi$\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7050-T7451	Plate	L-T	----	13	96	1.0-2.0	39	32	25	11.7	c
7050-T7451	Plate	T-L	≥1.0	9	97	0.5-2.0	38	28	21	15.6	c
7050-T7451	Plate	S-L	≥1.0	6	44	0.7-2.0	28	23	21	6.3	
7050-T7452	Hand Forging	L-T	3.5-5.5	1	11	1.5	34	31	26	8.0	c
7050-T7452	Hand Forging	T-L	3.5-7.5	1	13	1.5	22	21	18	6.7	c
7050-T7452	Hand Forging	S-L	3.5-7.5	1	17	0.8-1.5	21	19	16	7.5	
7050-T76511	Extrusion	L-T	----	2	38	0.6-2.0	40	31	27	7.8	c
7075-T651	Plate	L-T	≥0.6	7	99	0.5-2.0	30	26	20	7.6	c
7075-T651	Plate	T-L	≥0.5	5	135	0.4-2.0	27	22	18	8.9	
7075-T651	Plate	S-L	----	2	37	0.5-1.5	22	18	14	10.4	
7075-T6510	Extrusion	L-T	0.7-3.5	1	26	0.5-1.2	32	27	23	7.8	
7075-T6510	Extrusion	T-L	0.7-3.5	1	25	0.5-1.2	28	24	21	8.0	
7075-T6510	Forged Bar	L-T	0.7-5.0	1	13	0.6-2.0	35	29	24	11.6	
7075-T6510	Forged Bar	T-L	0.7-5.0	1	13	0.5-2.5	24	21	17	8.2	
7075-T73	Die Forging	T-L	≥0.5	1	22	0.5-0.8	25	21	18	9.9	
7075-T73	Hand Forging	L-T	----	2	10	1.0-1.5	39	31	29	8.8	
7075-T73	Hand Forging	T-L	≥1.0	2	14	1.0-1.5	27	23	20	9.0	
7075-T7351	Plate	L-T	≥1.0	8	65	0.5-2.0	36	30	25	8.2	
7075-T7351	Plate	T-L	≥0.5	6	56	0.5-2.0	47	27	21	20.1	
7075-T7351	Plate	S-L	≥0.5	3	20	0.5-1.5	38	22	17	32.5	
7075-T73511	Extrusion	T-L	1.0-7.0	1	19	0.9-1.0	22	20	19	3.7	
7075-T73511	Extrusion	L-T	≥0.9	3	28	0.7-2.0	43	35	31	9.4	
7075-T73511	Extrusion	T-L	≥0.7	3	35	0.5-1.8	35	23	12	20.3	
7075-T73511	Extrusion	S-L	≥0.5	3	15	0.4-1.0	22	20	17	9.0	
7075-T7352	Hand Forging	L-T	----	2	27	0.8-2.0	39	33	30	9.2	
7075-T7352	Hand Forging	T-L	≥0.8	3	20	0.8-2.0	33	26	23	9.9	
7075-T7651	Plate	L-T	≥0.8	6	82	0.5-2.0	43	29	22	17.8	
7075-T7651	Plate	T-L	≥0.5	7	96	0.5-2.0	28	23	20	7.6	
7075-T7651	Plate	S-L	≥0.5	5	28	0.4-0.8	20	18	15	7.7	
7075-T7651	Clad Plate	L-T	0.5-0.6	2	30	0.5-0.6	30	25	22	7.1	
7075-T7651	Clad Plate	T-L	0.5-0.6	2	56	0.5-0.6	28	24	21	7.7	
7075-T76511	Extrusion	L-T	1.3-7.0	4	11	1.2-2.0	41	35	31	11.0	
7075-T76511	Extrusion	T-L	1.2	3	42	0.6-2.0	36	23	20	15.5	

a These values are for information only.
b Refer to Figure 1.4.12.3 for definition of symbols.
c Varies with thickness.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]—Continued

Alloy/Temper	Product Form	Orientation[b]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi$\sqrt{in.}$ Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7175-T6/T6511	Extrusion	T-L	----	2	25	0.8-1.0	24	21	18	7.9	
7175-T651	Plate	L-T	----	1	17	0.7-0.8	30	26	24	9.2	
7175-T651	Plate	T-L	----	1	10	0.7-0.8	26	22	20	9.8	
7175-T6511	Extrusion	L-T	----	2	14	0.8-1.0	36	32	24	13.8	
7175-T7351	Plate	L-T	----	2	30	0.7-1.6	36	33	32	3.3	
7175-T7351	Plate	T-L	----	2	32	0.7-1.6	30	27	25	4.5	
7175-T73511	Extrusion	L-T	≥0.7	5	43	0.5-1.5	47	33	23	16.0	30
7175-T73511	Extrusion	T-L	≥0.5	5	43	0.5-1.5	35	25	20	10.9	22
7175-T74	Die Forging	L-T	≥0.5	3	14	0.5-1.0	38	30	22	15.0	27
7175-T74	Die Forging	T-L	≥0.5	2	13	0.5-1.0	33	24	21	15.7	21
7175-T74	Die Forging	S-L	≥0.5	4	41	0.5-0.8	31	26	20	8.6	21
7175-T74	Hand Forging	T-L	3.0-5.0	2	10	1.0-1.5	29	26	24	4.8	25
7175-T7651	Clad Plate	L-T	----	1	53	1.5	33	32	30	4.3	
7175-T7651	Clad Plate	T-L	----	1	50	0.6	28	27	25	3.1	
7175-T7651	Plate	L-T	----	1	12	1.5	32	32	31	1.7	
7175-T7651	Plate	T-L	----	1	11	1.5	26	25	24	3.3	
7175-T76511	Extrusion	L-T	1.4-3.8	2	48	0.6-2.0	39	33	27	10.7	
7175-T76511	Extrusion	T-L	≥0.6	4	49	0.6-1.8	31	22	20	9.8	
7475-T651	Plate	L-T	----	3	34	0.9-2.0	49	38	33	9.2	30
7475-T651	Plate	T-L	0.6-2.0	2	143	0.6-2.0	43	34	27	9.8	28
7475-T651	Plate	S-L	≥0.6	1	23	0.5-1.0	36	28	20	14.9	
7475-T7351	Plate	L-T	1.3-4.0	8	151	1.3-3.0	60	47	34	10.4	c
7475-T7351	Plate	T-L	≥1.3	7	132	0.7-3.0	50	37	29	10.4	c
7475-T7351	Plate	S-L	≥0.7	7	74	0.5-1.5	36	30	25	8.7	25
7475-T7651	Plate	L-T	1.0-2.0	4	10	1.0-2.0	46	41	36	6.2	33
7475-T7651	Plate	T-L	≥1.0	2	15	0.9-2.0	50	36	29	14.5	30

a These values are for information only.
b Refer to Figure 1.4.12.3 for definition of symbols.
c Varies with thickness.

The tensile and shear moduli of aluminum alloys also increase with decreasing temperature so that at -100, -320, and -423°F, they are approximately 5, 12, and 16 percent, respectively, above the room temperature values [Reference 3.1.2.1.7(f)].

3.1.2.1.8 *Elevated Temperatures* — In general, the strengths of aluminum alloys decrease and toughness increases with increase in temperature and with time at temperature above room temperature; the effect is generally greatest over the temperature range from 212 to 400°F. Exceptions to the general trends are tempers developed by solution heat treatment without subsequent aging, for which the initial elevated temperature exposure results in some age hardening and reduction in toughness; further time at temperature beyond that required to achieve peak hardness results in the aforementioned decrease in strength and increase in toughness [Reference 3.1.2.1.8].

3.1.2.2 *Physical Properties* — Where available from the literature, the average values of certain physical properties are included in the room-temperature tables for each alloy. These properties include density, ω, in lb/in.^{3}; the specific heat, C, in Btu/(lb)(°F); the thermal conductivity, K, in Btu/[(hr)(ft^2)(°F)/ft]; and the mean coefficient of thermal expansion, α, in in./in./°F. Where more extensive data are available to show the effect of temperature on these physical properties, graphs of physical property as a function of temperature are presented for the applicable alloys.

3.1.2.3 *Corrosion Resistance* —

3.1.2.3.1 *Resistance to Stress-Corrosion Cracking [see References 3.1.2.3.1(a) through (d)]* — The high-strength heat treatable wrought aluminum alloys in certain tempers are susceptible to stress-corrosion cracking, depending upon product, section size, direction and magnitude of stress. These alloys include 2014, 2025, 2618, 7075, 7150, 7175, and 7475 in the T6-type tempers and 2014, 2024, 2124, and 2219 in the T3 and T4-type tempers. Other alloy-temper combinations, notably 2024, 2124, 2219, and 2519 in the T6- or T8-type tempers and 7010, 7049, 7050, 7075, 7149, 7175, and 7475 in the T73-type tempers, are decidedly more resistant and sustained tensile stresses of 50 to 75 percent of the minimum yield strength may be permitted without concern about stress corrosion cracking. The T74 and T76 tempers of 7010, 7075, 7475, 7049, 7149, and 7050 provide an intermediate degree of resistance to stress-corrosion cracking, i.e., superior to that of the T6 temper, but not as good as that of the T73 temper of 7075. To assist in the selection of materials, letter ratings indicating the relative resistance to stress-corrosion cracking of various mill product forms of the wrought 2000, 6000, and 7000 series heat-treated aluminum alloys are presented in Table 3.1.2.3.1(a). This table is based upon ASTM G 64 which contains more detailed information regarding this rating system and the procedure for determining the ratings. In addition, more quantitative information in the form of the maximum specified tension stresses at which test specimens will not fail when subjected to the alternate immersion stress-corrosion test described in ASTM G 47 are shown in Tables 3.1.2.3.1(b) through (e) for various heat-treated aluminum product forms, alloys, and tempers.

Where short times at elevated temperatures of 150 to 500°F may be encountered, the precipitation heat-treated tempers of 2024 and 2219 alloys are recommended over the naturally aged tempers.

Alloys 5083, 5086, and 5456 should not be used under high constant applied stress for continuous service at temperatures exceeding 150°F, because of the hazard of developing susceptibility to stress-corrosion cracking. In general, the H34 through H38 tempers of 5086, and the H32 through H38 tempers of 5083 and 5456 are not recommended, because these tempers can become susceptible to stress-corrosion cracking.

For the cold forming of 5083 sheet and plate in the H112, H321, H323, and H343 tempers and 5456 sheet and plate in the H112 and H321 tempers, a minimum bend radius of 5T should be used. Hot forming of the O temper for alloys 5083 and 5456 is recommended, and is preferred to the cold worked

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
2014-T6	L	A	A	A	B
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
2024-T3, T4	L	A	A	A	[f]
	LT	B[e]	D	B[e]	[f]
	ST	D	D	D	[f]
2024-T6	L	[f]	A	[f]	A
	LT	[f]	B	[f]	A[e]
	ST	[f]	B	[f]	D
2024-T8	L	A	A	A	A
	LT	A	A	A	A
	ST	B	A	B	C
2124-T8	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	B	[f]	[f]	[f]
2219-T351X, T37	L	A	[f]	A	[f]
	LT	B	[f]	B	[f]
	ST	D	[f]	D	[f]
2219-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
2219-T85XX, T87	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	A	[f]	A	A
6061-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
7049-T73	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	A	[f]	B	A
7049-T76	L	[f]	[f]	A	[f]
	LT	[f]	[f]	A	[f]
	ST	[f]	[f]	C	[f]
7050-T74	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	B	[f]	B	B
7050-T76	L	A	A	A	[f]
	LT	A	B	A	[f]
	ST	C	B	C	[f]
7075-T6	L	A	A	A	A
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
7075-T73	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products—Continued

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
7075-T74	L	[f]	[f]	[f]	A
	LT	[f]	[f]	[f]	A
	ST	[f]	[f]	[f]	B
7075-T76	L	A	[f]	A	[f]
	LT	A	[f]	A	[f]
	ST	C	[f]	C	[f]
7149-T73	L	[f]	[f]	A	A
	LT	[f]	[f]	A	A
	ST	[f]	[f]	B	A
7175-T74	L	[f]	[f]	[f]	A
	LT	[f]	[f]	[f]	A
	ST	[f]	[f]	[f]	B
7475-T6	L	A	[f]	[f]	[f]
	LT	B[e]	[f]	[f]	[f]
	ST	D	[f]	[f]	[f]
7475-T73	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	A	[f]	[f]	[f]
7475-T76	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	C	[f]	[f]	[f]

a Ratings were determined from stress corrosion tests performed on at least ten random lots for which test results showed 95% conformance at the 95% confidence level when tested at the stresses indicated below. A practical interpretation of these ratings follows the rating definition.

A - Equal or greater than 75% of the specified minimum yield strength. Very high. No record of service problems and SCC not anticipated in general applications.

B - Equal or greater than 50% of the specified minimum yield strength. High. No record of service problems and SCC not anticipated at stresses of the magnitude caused by solution heat treatment. Precautions must be taken to avoid high sustained tensile stress exceeding 50% of the minimum specified yield strength produced by any combination of sources including heat treatment, straightening, forming, fit-up, and sustained service loads.

C - Equal or greater than 25% of the specified minimum yield strength. Intermediate. SCC not anticipated if the total sustained tensile strength is less than 25% of the minimum specified yield strength. This rating is designated for the short transverse direction in improved products used primarily for high resistance to exfoliation corrosion in relatively thin structures where applicable short transverse stresses are unlikely.

D - Fails to meet the criterion for the rating C. Low. SCC failures have occurred in service or would be anticipated if there is any sustained tensile stress in the designated test direction. This rating currently is designated only for the short transverse direction in certain materials.

NOTE - The above stress levels are not to be interpreted as "threshold" stresses, and are not recommended for design. Other documents, such as MIL-STD-1568, NAS SD-24, and MSFC-SPEC-522A, should be consulted for design recommendations.

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High Strength Aluminum Alloy Products—Continued

b The ratings apply to standard mill products in the types of tempers indicated, including stress-relieved tempers, and could be invalidated in some cases by application of nonstandard thermal treatments of mechanical deformation at room temperature by the user.

c Test direction refers to orientation of the stressing direction relative to the directional grain structure typical of wrought materials, which in the case of extrusions and forgings may not be predictable from the geometrical cross section of the product.
L—Longitudinal: parallel to the direction of principal metal extension during manufacture of the product.
LT—Long Transverse: perpendicular to direction of principal metal extension. In products whose grain structure clearly shows directionality (width to thickness ratio greater than two) it is that perpendicular direction parallel to the major grain dimension.
ST—Short Transverse: perpendicular to direction of principal metal extension and parallel to minor dimension of grains in products with significant grain directionality.

d Sections with width-to-thickness ratio equal to or less than two for which there is no distinction between LT and ST.

e Rating is one class lower for thicker sections: extrusion, 1 inch and over; plate and forgings, 1.5 inches and over.

f Ratings not established because the product is not offered commercially.

NOTE: This table is based upon ASTM G 64.

Table 3.1.2.3.1(b). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[d] for Various Stress Corrosion Resistant Aluminum Alloy Plate

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
2024-T851	ST	1.001-4.000	28[a]	Company specification
		4.001-6.000	27[a]	
2090-T81[c]	ST	0.750-1.500	20	AMS 4303
2124-T851	ST	1.500-1.999	28[a]	AMS 4101
		2.000-4.000	28[a]	AMS-QQ-A-0025/29, ASTM B 209, AMS 4101
		4.001-6.000	27[a]	
2124-T8151[c]	ST	1.500-3.000	30[a]	AMS 4221
		3.001-5.000	29[a]	
		5.001-6.000	28[a]	
2219-T851	ST	0.750-2.000	34[b]	AMS-QQ-A-250/30
		2.001-4.000	33[b]	
		4.001-5.000	32[b]	
		5.001-6.000	31[b]	
2219-T87	ST	0.750-3.000	38[b]	AMS-QQ-A-250/30
		3.001-4.000	37[b]	
		4.001-5.000	36[b]	
2519-T87	ST	0.750-4.000	43[b]	MIL-A-46192
7010-T7351[c]	ST	0.750-3.000	41[b]	AMS 4203
		3.001-5.000	40[b]	
		5.001-5.500	39[b]	
7010-T7451	ST	0.750-3.000	31[a]	AMS 4205
		3.001-5.500	35	
7010-T7651	ST	0.750-5.500	25	AMS 4204
7049-T7351	ST	0.750-5.000	45	AMS 4200
7050-T7451	ST	0.750-6.000	35	AMS 4050
7050-T7651	ST	0.750-3.000	25	AMS 4201
7075-T7351	ST	0.750-2.000	42[b]	AMS-QQ-A-250/12, AMS 4078, ASTM B 209
		2.001-2.500	39[b]	
		2.501-4.000	36[b]	
7075-T7651	ST	0.750-1.000	25	AMS-QQ-A-00250/24, ASTM B 209
Clad 7075-T7651	ST	0.750-1.000	25	AMS-QQ-A-00250/25, ASTM B 209
7150-T7751	ST	0.750-3.000	25	AMS 4252
7475-T7351	ST	0.750-4.000	40	AMS 4202
7475-T7651	ST	0.750-1.500	25	AMS 4089

a 50% of specified minimum long transverse yield strength.

b 75% of specified minimum long transverse yield strength.

c Design values are not included in MIL-HDBK-5.

d Most specifications reference ASTM G 47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.

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Table 3.1.2.3.1(c). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[e] for Various Stress Corrosion Resistant Aluminum Alloy Rolled Bars, Rods, and Extrusions

Alloy and Temper	Product Form	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7075-T73-T7351	Rolled Bar and Rod	ST	0.750-3.000	42[a]	AMS-QQ-A-225/9, AMS 4124, ASTM B211
2219-T8511	Extrusion	ST	0.750-3.000	30	AMS 4162, AMS 4163
7049-T73511	Extrusion	ST	0.750-2.999	41[b]	AMS 4157
			3.000-5.000	40[b]	
7049-T76511[d]	Extrusion	ST	0.750-5.000	20	AMS 4159
7050-T73511	Extrusion	ST	0.750-5.000	45	AMS 4341
7050-T74511	Extrusion	ST	0.750-5.000	35	AMS 4342
7050-T76511	Extrusion	ST	0.750-5.000	17	AMS 4340
7075-T73-T73510-T73511	Extrusion	ST	0.750-1.499	45[a]	AMS-QQ-A-200/11, AMS 4166, AMS 4167, ASTM B 211
			1.500-2.999	44[a]	
			3.000-4.999	42[a]	
			3.000-4.999	41[a,c]	
7075-T76-T76510-T76511	Extrusion	ST	0.750-1.000	25	AMS-QQ-A-200/15, ASTM B 221
7149-T73511[d]	Extrusion	ST	0.750-2.999	41[b]	AMS 4543
			3.000-5.000	40[b]	
7150-T77511	Extrusion	ST	0.750-2.000	25	AMS 4345
7175-T73511	Extrusion	ST	0.750-2.000	44	AMS 4344

a 75% of specified minimum longitudinal yield strength.
b 65% of specified minimum longitudinal yield strength.
c Over 20 square inches cross-sectional area.
d Design values are not included in MIL-HDBK-5.
e Most specifications reference ASTM G 47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.

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Table 3.1.2.3.1(d). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[d] for Various Stress Corrosion Resistant Aluminum Die Forgings

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	0.750-2.000	46[a]	QQ-A-367, AMS 4111, ASTM B 247
		2.001-5.000	45[a]	
7050-T74	ST	0.750-6.000	35	AMS 4107
7050-T7452	ST	0.750-4.000	35	AMS 4333
7075-T73	ST	0.750-3.000	42[a]	MIL-A-22771, QQ-A-367
		3.001-4.000	41[a]	AMS 4241, ASTM B 247
		4.001-5.000	39[a]	AMS 4141
		5.001-6.000	38[a]	
7075-T7352	ST	0.750-4.000	42[a]	MIL-A-22771, QQ-A-367, AMS 4147, ASTM B 247
		3.001-4.000	39[a]	
7075-T7354[c]	ST	0.750-3.000	42	Company Specification
7075-T74[c]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	31[b]	
		4.001-5.000	30[b]	
		5.001-6.000	29[b]	
7149-T73	ST	0.750-2.000	46[a]	AMS 4320
		2.001-5.000	45[a]	
7175-T74	ST	0.750-3.000	35	AMS 4149, ASTM B 247
		3.001-4.000	31[b]	AMS 4149
		4.001-5.000	30[b]	
		5.001-6.000	29[b]	
7175-T7452[c]	ST	0.750-3.000	35	AMS 4179

a 75% of specified minimum longitudinal yield strength.
b 50% of specified minimum longitudinal yield strength.
c Design values are not included in MIL-HDBK-5.
d Most specifications Reference ASTM G 47, which requires 20 days of exposure for 7XXX alloys in ST test direction.

DO NOT USE STRESS VALUES FOR DESIGN

Table 3.1.2.3.1(e). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[f] for Various Stress Corrosion Resistant Aluminum Hand Forgings

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	2.001-3.000	45[a]	QQ-A-367, AMS 4111, ASTM B 247
		3.001-4.000	44[a]	
		4.001-5.000	42[a]	
7049-T7352[e]	ST	0.750-3.000	44[a]	AMS 4247
		3.001-4.000	43[a]	
		4.001-5.000	40[a]	
7050-T7452	ST	0.750-8.000	35	AMS 4108
7075-T73	ST	0.750-3.000	42[a]	MIL-A-22771, QQ-A-367, ASTM B 247
		3.001-4.000	41[a]	
		4.001-4.000	39[a]	
		5.001-6.000	38[a]	
7075-T7352	ST	0.750-3.000	39[c]	AMS 4147
		3.001-4.000	37[c]	
		4.001-5.000	36[c]	
		5.001-6.000	34[c]	
7075-T74[e]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	30[b]	
		4.001-5.000	28[b]	
		5.001-6.000	27[b]	
7075-T7452[e]	ST	0.750-2.000	35	AMS 4323
		2.001-3.000	29[d]	
		3.001-4.000	28[d]	
		4.001-5.000	26[d]	
		5.001-6.000	24[d]	
7149-T73	ST	2.000-3.000	44[c]	AMS 4320
		3.001-4.000	43[c]	
		4.001-5.000	42[c]	
7175-T74	ST	0.750-3.000	35	AMS 4149
		3.001-4.000	29[d]	
		4.001-5.000	28[d]	
		4.001-6.000	26[d]	
7175-T7452	ST	0.750-3.000	35	AMS 4179
		3.001-4.000	27[d]	
		4.001-5.000	26[d]	
		5.001-6.000	24[d]	

a 75% of specified minimum longitudinal yield strength.
b 50% of specified minimum longitudinal yield strength.
c 75% of specified minimum long transverse yield strength.
d 50% of specified minimum long transverse yield strength.
e Design values are not included in MIL-HDBK-5.
f Most specifications Reference ASTM G 47, which requires 20 days of exposure for 7XXX alloys in ST test direction.

DO NOT USE STRESS VALUES FOR DESIGN

tempers to avoid excessive cold work and high residual stress. If the cold worked tempers are heat-treatable alloys are heated for hot forming, a slight decrease in mechanical properties, particularly yield strength, may result.

3.1.2.3.2 *Resistance to Exfoliation [Reference 3.1.2.3.2]* — The high-strength wrought aluminum alloys in certain tempers are susceptible to exfoliation corrosion, dependent upon product and section size. Generally those alloys and tempers that have the lowest resistance to stress-corrosion cracking also have the lowest resistance to exfoliation. The tempers that provide improved resistance to stress-corrosion cracking also provide improved resistance or immunity to exfoliation. For example, the T76 temper of 7075, 7049, 7050, and 7475 provides a very high resistance to exfoliation, i.e., decidedly superior to the T6 temper, and almost the immunity provided by the T73 temper of 7075 alloy (see Reference 3.1.2.3.2).

3.1.3 MANUFACTURING CONSIDERATIONS

3.1.3.1 *Avoiding Stress-Corrosion Cracking* — In order to avoid stress-corrosion cracking (see Section 3.1.2.3), practices, such as the use of press or shrink fits; taper pins; clevis joints in which tightening of the bolt imposes a bending load on female lugs; and straightening or assembly operations; which result in sustained surface tensile stresses (especially when acting in the short-transverse grain orientation), should be avoided in these high-strength alloys: 2014-T451, T4, T6, T651, T652; 2024-T3, T351, T4; 7075-T6, T651, T652; 7150-T6151, T61511; and 7475-T6, T651.

Where straightening or forming is necessary, it should be performed when the material is in the freshly quenched condition or at an elevated temperature to minimize the residual stress induced. Where elevated temperature forming is performed on 2014-T4 T451, or 2024-T3 T351, a subsequent precipitation heat treatment to produce the T6 or T651, T81 or T851 temper is recommended.

It is good engineering practice to control sustained short-transverse tensile stress at the surface of structural parts at the lowest practicable level. Thus, careful attention should be given in all stages of manufacturing, starting with design of the part configuration, to choose practices in the heat treatment, fabrication, and assembly to avoid unfavorable combinations of end grain microstructure and sustained tensile stress. The greatest danger arises when residual, assembly, and service stress combine to produce high sustained tensile stress at the metal surface. Sources of residual and assembly stress have been the most contributory to stress-corrosion-cracking problems because their presence and magnitude were not recognized. In most cases, the design stresses (developed by functional loads) are not continuous and would not be involved in the summation of sustained tensile stress. It is imperative that, for materials with low resistance to stress-corrosion cracking in the short-transverse grain orientation, every effort be taken to keep the level of sustained tensile stress close to zero.

3.1.3.2 *Cold-Formed Heat-Treatable Aluminum Alloys* — Cold working such as stretch forming of aluminum alloy prior to solution heat treatment may result in recrystallization or grain growth during heat treatment. The resulting strength, particularly yield strength, may be significantly below the specified minimum values. For critical applications, the strength should be determined on the part after forming and heat treating including straightening operations. To minimize recrystallization during heat treatment, it is recommended that forming be done after solution heat treatment in the as-quenched condition whenever possible, but this may result in compressive yield strength in the direction of stretching being lower than MIL-HDBK-5 design allowables for user heat treat tempers.

3.1.3.3 *Dimensional Changes* — The dimensional changes that occur in aluminum alloy during thermal treatment generally are negligible, but in a few instances these changes may have to be considered in manufacturing. Because of many variables involved, there are no tabulated values for these dimensional changes. In the artificial aging of alloy 2219 from the T42, T351, and T37 tempers to the T62, T851, and T87 tempers, respectively, a net dimensional growth of 0.00010 to 0.0015 in./in. may be anticipated. Additional growth of as much as 0.0010 in./in. may occur during subsequent service of a year or more at 300°F or equivalent shorter exposures at higher temperatures. The dimensional changes that occur during the artificial aging of other wrought heat-treatable alloys are less than one-half that for alloy 2219 under the same conditions.

3.1.3.4 *Welding* — The ease with which aluminum alloys may be welded is dependent principally upon composition, but the ease is also influenced by the temper of the alloy, the welding process, and the filler metal used. Also, the weldability of wrought and cast alloys is generally considered separately.

Several weldability rating systems are established and may be found in publications by the Aluminum Association, American Welding Society, and the American Society for Metals. Handbooks from these groups can be consulted for more detailed information. Specification AA-R-566 also contains useful information. This document follows most of these references in adopting a four level rating system. An “A” level, or readily weldable, means that the alloy (and temper) is routinely welded by the indicated process using commercial procedures. A “B” level means that welding is accomplished for many applications, but special techniques are required, and the application may require preliminary trials to develop procedures and tests to demonstrate weld performance. A “C” level refers to limited weldability because crack sensitivity, loss of corrosion resistance, and/or loss of mechanical properties may occur. A “D” level indicates that the alloy is not commercially weldable.

The weldability of aluminum alloys is rated by alloy, temper, and welding process (arc or resistance). Tables 3.1.3.4(a) and (b) list the ratings in the alloy section number order in which they appear in Chapter 3.

When heat-treated or work-hardened materials of most systems are welded, a loss of mechanical properties generally occurs. The extent of the loss (if not reheat treated) over the table strength allowables will have to be established for each specific situation.

Table 3.1.3.4(a). Fabrication Weldability of Wrought Aluminum Alloys

MIL-HDBK-5 Section No.	Alloy	Tempers	Weldability[a,c] Inert Gas Metal or Tungsten Arc	Resistance Spot[b]
3.2.1	2014	O	C	D
		T6, T62, T651, T652, T6510, T6511	B	B
3.2.2	2017	T4, T42, T451	C	B
3.2.3	2024	O	D	D
		T3, T351, T361, T4, T42	C	B
		T6, T62, T81, T851, T861	C	B
		T8510, T8511, T3510, T3511	C	B
3.2.4	2025	T6	C	B
3.2.5	2090	T83	B	B
3.2.6	2124	T851	C	B
3.2.7	2219	O	A	B-D
		T62, T81, T851, T87, T8510, T8511	A	A
3.2.8	2618	T61	C	B
3.2.9	2519	T87	A	...
3.5.1	5052	O	A	B
		H32, H34, H36, H38	A	A
3.5.2	5083	O	A	B
		H321, H323, H343, H111, H112	A	A
3.5.3	5086	O	A	B
		H32, H34, H36, H38, H111, H112	A	A
3.5.4	5454	O	A	B
		H32, H34, H111, H112	A	A
3.5.5	5456	O	A	B
		H111, H321, H112	A	A
3.6.1	6013	T6	A	A
3.6.2	6061	O	A	B
		T4, T42, T451, T4510, T4511, T6	A	A
		T62, T651, T652, T6510, T6511	A	A
3.6.3	6151	T6	A	A
3.7.1	7010	All	C	B
3.7.2	7049	All	C	B
	7149			
3.7.3	7050	All	C	B
3.7.4	7075	All	C	B
3.7.5	7150	All	C	B
3.7.6	7175	All	C	B
3.7.7	7475	All	C	B

a Ratings A through D are relative ratings defined as follows:
A - Generally weldable by all commercial procedures and methods.
B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedures and weld performance.
C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
D - No commonly used welding methods have been developed.

b See MIL-W-6858 for permissible combinations.

c When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

Table 3.1.3.4(b). Fabrication Weldability[a] of Cast Aluminum Alloys

MIL-HDBK-5 Section No.	Alloy	Weldability[b,c]	
		Inert Gas Metal or Tungsten Arc	Resistance Spot
3.8.1	A201.0	C	C
3.9.1	354.0	B	B
3.9.2	355.0	B	B
3.9.3	C355.0	B	B
3.9.4	356.0	A	A
3.9.5	A356.0	A	A
3.9.6	A357.0	A	B
3.9.7	D357.0	A	A
3.9.8	359.0	A	B

a Weldability related to joining a casting to another part of same composition. The weldability ratings are not applicable to minor weld repairs. Such repairs shall be governed by the contractors procedure for in-process welding of castings, after approval by the procuring agency.

b Ratings A through D are relative ratings defined as follows:

A - Generally weldable by all commercial procedures and methods.

B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedure and weld performance.

C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.

D - No commonly used welding methods have been developed.

c When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

CHAPTER 4

MAGNESIUM ALLOYS

4.1 GENERAL

This chapter contains the engineering properties and characteristics of wrought and cast magnesium alloys used in aircraft and missile applications. Magnesium is a lightweight structural metal that can be strengthened greatly by alloying, and in some cases by heat treatment or cold work or by both.

4.1.1 ALLOY INDEX — The magnesium alloys in this chapter are listed in alphanumeric sequence in each of two parts, the first one being wrought forms of magnesium and the second cast forms. These sections and the alloys covered under each are shown in Table 4.1.

Table 4.1. Magnesium Alloys Index

Section	Designation
4.2	**Magnesium-Wrought Alloys**
4.2.1	AZ31B
4.2.2	AZ61A
4.2.3	ZK60A
4.3	**Magnesium-Cast Alloys**
4.3.1	AM100A
4.3.2	AZ91C/AZ91E
4.3.3	AZ92A
4.3.4	EZ33A
4.3.5	QE22A
4.3.6	ZE41A

4.1.2 MATERIAL PROPERTIES

4.1.2.1 *Mechanical Properties* — The mechanical properties are given either as design values or for information purposes. The tensile strength (F_{tu}), tensile yield strength (F_{ty}), elongation (e), and sometimes the compressive yield strength (F_{cy}) are guaranteed by procurement specifications. The properties obtained reflect the location of sample, type of test specimen and method of testing required by the product specification. The remaining design values are "derived" values; that is, sufficient tests have been made to ascertain that if a given material meets the requirements of the product specification, the material will have the compression (F_{cy}), shear (F_{su}) and bearing (F_{bru} and F_{bry}) strengths listed.

4.1.2.1.1 *Tension Testing* — Room-temperature tension tests are made according to ASTM E 8. The yield strength (F_{ty}) is obtained by the "offset method" using an offset of 0.2 percent. The speed of testing for room-temperature tests has a small effect on the strength and elongation values obtained on most magnesium alloys. The rate of stressing generally specified to the yield strength is less than 100,000 psi per minute and the rate of straining from the yield strength to fracture is less than 0.5 in./in./min. It can be expected that the speed of testing used for room-temperature tension tests will approach the maximum permitted.

Elevated-temperature tension tests are made according to ASTM E 21. The speed of testing has a considerable effect on the results obtained and no one standard rate of straining is given in ASTM E 21. The strain rates most commonly used on magnesium are 0.005 in./in./min. to the yield and 0.10 in./in./min. from yield to fracture [see References 4.1.2.1.1(a) to (d)].

4.1.2.1.2 *Compression Testing* — Compression test methods used for magnesium are specified in ASTM E 9. The values given for the compressive yield strength (F_{cy}), are taken at an offset of 0.2 percent. References 4.1.2.1.2(a) and (b) provide information on test techniques.

4.1.2.1.3 *Bearing Testing* — Bearing tests of magnesium alloys are made according to ASTM E 238. The size of pin used has a significant effect on the values obtained, especially the bearing ultimate strength (F_{bru}). On tests made to obtain the data on magnesium alloys shown in this document, pin diameters of 0.187 and 0.250 inch were used. For pin diameters significantly larger than 0.250 inch lower values may be obtained. Additional information on bearing testing is given in References 4.1.2.1.3(a) and (b). Bearing values in the property tables are considered to be "dry pin" values in accordance with the discussion in Section 1.4.7.1.

4.1.2.1.4 *Shear Testing* — The shear strength values used in this document were obtained by the "double shear" method using a pin-type specimen, the "punch shear" method and the "tension shear" method as applicable. Just as tensile ultimate strength (F_{tu}) values vary with location and direction of sample in relation to the method of fabrication, the shear strength (F_{su}) may be expected to reflect the effect of orientation, either as a function of the sampling or the maximum stresses imposed by the method of test. Information on shear testing is given in Reference 4.1.2.1.4.

4.1.2.1.5 *Shear Raisers* — The effect of notches, holes, and stress raisers on the static properties of magnesium alloys is described in References 4.1.2.1.5(a) through (c). Additional data on the strength properties of magnesium alloys are presented in References 4.1.2.1.5(d) through (h).

4.1.2.1.6 *Creep* — Some creep data on magnesium alloys are summarized in Reference 4.1.2.1.6.

4.1.2.1.7 *Fatigue* — Room-temperature axial load fatigue data for several magnesium alloys are presented in appropriate alloy sections. References 4.1.2.1.7(a) and (b) provide additional data on fatigue of magnesium alloys.

4.1.3 PHYSICAL PROPERTIES — Selected experimental data from the literature were used in determining values for physical properties. In other cases, enough information was available to calculate the constants. Estimated values of some of the remaining constants were also included. Estimated values are noted.

4.1.4 ENVIRONMENTAL CONSIDERATIONS — Corrosion protection must be considered for all magnesium applications. Protection can be provided by anodic films, chemical conversion coatings, paint systems, platings, or a combination of these methods. Proper drainage must be provided to prevent entrapment of water or other fluids. Dissimilar metal joints must be properly and completely insulated, including barrier strips and sealants.

Strain-hardened or age-hardened alloys may be annealed or overaged by prolonged exposure to elevated temperatures, with a resulting decrease in strength. Maximum recommended temperatures for prolonged service are reported, where available, for specific alloys.

4.1.5 ALLOY AND TEMPER DESIGNATIONS — Standard ASTM nomenclature is used for the alloys listed. Temper designations are given in ASTM B 296. A summary of the temper designations is given in Table 4.1.5.

4.1.6 JOINING METHODS — Most magnesium alloys may be welded; refer to "Comments and Properties" in individual alloy sections. Adhesive bonding and brazing may be used to join magnesium to itself or other alloys. All types of mechanical fasteners may be used to join magnesium. Refer to Section 4.1.4 when using mechanical fasteners or joining of dissimilar materials with magnesium alloys.

Table 4.1.5. Temper Designation System for Magnesium Alloys

Temper Designation System[a]

This temper designation system is used for all forms of wrought and cast magnesium and magnesium alloy products except ingots. It is based on the sequence of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

NOTE—In material specifications containing reference to two or more tempers of the same alloy which result in identical mechanical properties, the distinction between the tempers should be covered in suitable explanatory notes.

Basic Temper Designations

F **as fabricated.** Applies to the products of shaping processes in which no special control over thermal conditions or strain-hardening is employed.

O **annealed recrystallized (wrought products only).** Applies to wrought products which are annealed to obtain the lowest strength temper.

H **strain-hardened (wrought products only).** Applies to products which have their strength increased by strain-hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W **solution heat-treated.** An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated: for example, W ½ hr.

T **thermally treated to product stable tempers other than F, O, or H.** Applies to products which are thermally treated, with or without supplementary strain-hardening, to product stable tempers. The T is always followed by one or more digits.

Subdivisions of H Temper: Strain-Hardened

The first digit following H indicates the specific combination of basic operations, as follows:

H1 **strain-hardened only.** Applies to products which are strain-hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

H2 **strain-hardened and partially annealed.** Applies to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

H3 **strain-hardened and stabilized.** Applies to products which are strain-hardened and whose mechanical properties are stabilized by a low temperature thermal treatment to slightly lower strength and increase ductility. The number following this designation indicates the degree of strain-hardening remaining after the stabilization treatment.

The digit following the designations H1, H2, and H3 indicates the final degree of strain hardening. Tempers between 0 (annealed) and 8 (full-hard) are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between

a From ASTM B 296.

Table 4.1.5. Temper Designation System for Magnesium Alloys (Continued)

that of the 0 temper and that of the 8 temper is designated by the numeral 4; about midway between the 0 and 4 tempers by the numeral 2; and about midway between 4 and 8 tempers by the numeral 6, etc. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper.

The third digit, when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties or both differ from, but are close to, that (or those) for the two-digit H temper designation to which it is added. Numerals 1 through 9 may be arbitrarily assigned as the third digit for an alloy and product to indicate a specific degree of control of temper or special mechanical property limits.

**Subdivisions of T Temper:
Thermally Treated**

Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows.

T1 **cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.** Applies to products for which the rate of cooling from an elevated temperature shaping process, such as casting or extrusion, is such that their strength is increased by room temperature aging.

T2 **annealed (castings only).** Applies to a type of annealing treatment used to improve ductility and increase stability.

T3 **solution heat-treated and cold worked.** Applies to products which are cold worked to improve strength after solution heat-treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T4 **solution heat-treated and naturally aged to a substantially stable condition.** Applies to products which are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T5 **cooled from an elevated temperature shaping process and artificially aged.** Applies to products which are cooled from an elevated temperature shaping process, such as casting or extrusion, and artificially aged to improve mechanical properties or dimensional stability or both.

T6 **solution heat-treated and artificially aged.** Applies to products which are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7 **solution heat-treated and stabilized.** Applies to products that are stabilized after solution heat-treatment to carry them beyond a point of maximum strength to provide control of some special characteristic.

T8 **solution heat-treated, cold worked, and artificially aged.** Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9 **solution heat-treated, artificially aged, and cold worked.** Applies to products which are cold worked to improve strength.

T10 **cooled from an elevated temperature shaping process, artificially aged, and cold worked.** Applies to products which are artificially aged after cooling from an elevated temperature shaping process, such as extrusion, and cold worked to further improve strength.

Additional digits, the first of which shall not be zero, may be added to designations T1 through T10 to indicate a variation in treatment which significantly alters the product characteristics[b] that are or would be obtained using the basic treatment.

b For this purpose, characteristic is something other than mechanical properties.

CHAPTER 5

TITANIUM

5.1 GENERAL

This chapter contains the engineering properties and related characteristics of titanium and titanium alloys used in aircraft and missile structural applications.

General comments on engineering properties and the considerations relating to alloy selection are presented in Section 5.1. Mechanical- and physical-property data and characteristics pertinent to specific alloy groups or individual alloys are reported in Sections 5.2 through 5.5.

Titanium is a relatively lightweight, corrosion-resistant structural material that can be strengthened greatly through alloying and, in some of its alloys, by heat treatment. Among its advantages for specific applications are: good strength-to-weight ratio, low density, low coefficient of thermal expansion, good corrosion resistance, good oxidation resistance at intermediate temperatures, good toughness, and low heat-treating temperature during hardening, and others.

5.1.1 TITANIUM INDEX — The coverage of titanium and its alloys in this chapter has been divided into four sections for systematic presentation. The system takes into account unalloyed titanium and three groups of alloys based on metallurgical differences which in turn result in differences in fabrication and property characteristics. The sections and the individual alloys covered under each are shown in Table 5.1.

5.1.2 MATERIAL PROPERTIES — The material properties of titanium and its alloys are determined mainly by their alloy content and heat treatment, both of which are influential in determining the allotropic forms in which this material will be bound. Under equilibrium conditions, pure titanium has an "alpha" structure up to 1620°F, above which it transforms to a "beta" structure. The inherent properties of these two structures are quite different. Through alloying and heat treatment, one or the other or a combination of these two structures can be made to exist at service temperatures, and the properties of the material vary accordingly. References 5.1.2(a) and (b) provide general discussion of titanium microstructures and associated metallography.

Table 5.1. Titanium Alloys Index

Section	Alloy Designation
5.2	**Unalloyed Titanium**
5.2.1	Commercially Pure Titanium
5.3	**Alpha and Near-Alpha Titanium Alloys**
5.3.1	Ti-5A1-2.5Sn (Alpha)
5.3.2	Ti-8A1-1Mo-1V (Near-Alpha)
5.3.3	Ti-6A1-2Sn-4Zr-2Mo (Near-Alpha)
5.4	**Alpha-Beta Titanium Alloys**
5.4.1	Ti-6A1-4V
5.4.2	Ti-6A1-6V-2Sn
5.5	**Beta, Near-Beta, and Metastable Titanium Alloys**
5.5.1	Ti-13V-11Cr-3A1
5.5.2	Ti-15V-3Cr-3Sn-3A1
5.5.3	Ti-10V-2Fe-3A1

Titanium and titanium alloys of the alpha and alpha-beta type exhibit crystallographic textures in sheet form in which certain crystallographic planes or directions are closely aligned with the direction of prior working. The presence of textures in these materials lead to anisotropy with respect to many mechanical and physical properties. Poisson's ratio and Young's modulus are among those properties strongly affected by texture. Wide variations experienced in these properties both within and between sheets of titanium alloys have been qualitatively related to variations of texture. In general, the degree of texturing, and hence the variation of Young's modulus and Poisson's ratio, that is developed for alpha-beta alloys tends to be less than that developed in all alpha titanium alloys. Rolling temperature has a pronounced effect on the texturing of titanium alloys which may not in general be affected by subsequent thermal treatments. The degree of applicability of the effect of textural variations discussed above on the mechanical properties of products other than sheet is unknown at present. The values of Young's modulus and Poisson's ratio listed in this document represent the usual values obtained on products resulting from standard mill practices. References 5.1.2(c) and (d) provide further information on texturing in titanium alloys.

5.1.2.1 *Mechanical Properties* —

5.1.2.1.1 *Fracture Toughness* — The fracture toughness of titanium alloys is greatly influenced by such factors as chemistry variations, heat treatment, microstructure, and product thickness, as well as yield strength. For fracture critical applications, these factors should be closely controlled. Typical values of plane-strain fracture toughness for titanium alloys are presented in Table 5.1.2.1.1. Minimum, average, and maximum values, as well as coefficient of variation, are presented for various products for which valid data are available, but these values do not have the statistical reliability of the room-temperature mechanical properties.

5.1.3 MANUFACTURING CONSIDERATIONS — Comments relating to formability, weldability, and final heat treatment are presented under individual alloys. These comments are necessarily brief and are intended only to aid the designer in the selection of an alloy for a specific application. In practice, departures from recommended practices are very common and are based largely on in-plant experience. Springback is nearly always a factor in hot or cold forming.

Final heat treatments that are indicated as "specified" heat treatments do not necessarily coincide with the producers' recommended heat treatments. Rather, these treatments, along with the specified room-temperature minimum tensile properties, are contained in the heat treating-capability requirements of applicable specifications, for example, MIL-H-81200. Departures from the specified aging cycles are often necessary to account for aging that may take place during hot working or hot sizing or to obtain more desirable mechanical properties, for example, improved fracture toughness. More detailed recommendations for specific applications are generally available from the material producers.

5.1.4 ENVIRONMENTAL CONSIDERATIONS — Comments relating to temperature limitations in the application of titanium and titanium alloys are presented under the individual alloys.

Below about 300°F, as well as above about 700°F, creep deformation of titanium alloys can be expected at stresses below the yield strength. Available data indicate that room-temperature creep of unalloyed titanium may be significant (exceed 0.2 percent creep-strain in 1,000 hours) at stresses that exceed approximately 50 percent F_{ty}, room-temperature creep of Ti-5A1-1.5Sn ELI may be significant at stresses above approximately 60 percent F_{ty}, and room-temperature creep of the standard grades of titanium alloys may be significant at stresses above approximately 75 percent F_{ty}. References 5.1.4(a) through (c) provide some limited data regarding room-temperature creep of titanium alloys.

The use of titanium and its alloys in contact with either liquid oxygen or gaseous oxygen at cryogenic temperatures should be avoided, since either the presentation of a fresh surface (such as produced by tensile rupture) or impact may initiate a violent reaction [Reference 5.1.4(d)]. Impact of the surface in contact with liquid oxygen will result in a reaction at energy levels as low as 10 ft-lb. In gaseous oxygen, a partial pressure of about 50 psi is sufficient to ignite a fresh titanium surface over the temperature range from -250°F to room temperature or higher.

Titanium is susceptible to stress-corrosion cracking in certain anhydrous chemicals including methyl alcohol and nitrogen tetroxide. Traces of water tend to inhibit the reaction in either environment. However, in N_2O_4, NO is preferred and inhibited N_2O_4 contains 0.4 to 0.8 percent NO. Red fuming nitric acid with less than 1.5 percent water and 10 to 20 percent NO_2 can crack the metal and result in a pyrophoric reaction.

Titanium alloys are also susceptible to stress corrosion by dry sodium chloride at elevated temperatures. This problem has been observed largely in laboratory tests at 450 to 500°F and higher and occasionally in fabrication shops. However, there have been no reported failures of titanium components in service by hot salt stress corrosion. Cleaning with a nonchlorinated solvent (to remove salt deposits, including fingerprints) of parts used above 450°F is recommended.

In laboratory tests, with a fatigue crack present in the specimen, certain titanium alloys show an increased crack propagation rate in the presence of water or salt water as compared with the rate in air. These alloys also may show reduced sustained load-carrying ability in aqueous environments in the presence of fatigue cracks. Crack growth rates in salt water are a function of sheet or section thickness. These alloys are not susceptible in the form of thin-gauge sheet, but become susceptible as thickness increases. The thickness at which susceptibility occurs varies over a visual range with the alloy and processing. Alloys of titanium found susceptible to this effect include some from alpha, alpha-beta, and beta-type microstructures. In some cases, special processing techniques and heat treatments have been developed that minimize this effect. References 5.1.4(e) through (g) present detailed summaries of corrosion and stress corrosion of titanium alloys.

Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Table 5.1.2.1.1. Values of Room Temperature Plain-Strain Fracture Toughness of Titanium Alloys[a]

									K_{Ic}, ksi $\sqrt{in.}$			
Alloy	Heat Treat Condition	Product Form	Orientation[b]	Yield Strength Range, ksi	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	Max.	Avg.	Min.	Coefficient of Variation
Ti-6Al-4V	Mill Annealed	Forged Bar	L-T	121-143	<3.5	2	43	0.6-1.1	77	60	38	10.5
Ti-6Al-4V	Mill Annealed	Forged Bar	T-L	124-145	<3.5	2	64	0.5-1.3	81	57	33	11.7

a These values are for information only.
b Refer to Figure 1.4.12.3 for definition of symbols.

CHAPTER 6

HEAT-RESISTANT ALLOYS

6.1 GENERAL

Heat-resistant alloys are arbitrarily defined as iron alloys richer in alloy content than the 18 percent chromium, 8 percent nickel types, or as alloys with a base element other than iron and which are intended for elevated-temperature service. These alloys have adequate oxidation resistance for service at elevated temperatures and are normally used without special surface protection. So-called “refractory” alloys that require special surface protection for elevated-temperature service are not included in this chapter.

This chapter contains strength properties and related characteristics of wrought heat-resistant alloy products used in aerospace vehicles. The strength properties are those commonly used in structural design, such as tension, compression, bearing, and shear. The effects of elevated temperature are presented. Factors such as metallurgical considerations influencing the selection of metals are included in comments preceding the specific properties of each alloy or alloy group. Data on creep, stress-rupture, and fatigue strength, as well as crack-growth characteristics, are presented in the applicable alloy section.

There is no standardized numbering system for the alloys in this chapter. For this reason, each alloy is identified by its most widely accepted trade designation.

For convenience in presenting these alloys and their properties, the heat-resistant alloys have been divided into three groups, based on alloy composition. These groups and the alloys for which specifications and properties are included are shown in Table 6.1.

The heat treatments applied to the alloys in this chapter vary considerably from one alloy to another. For uniformity of presentation, the heat-treating terms are defined as follows:

Stress-Relieving — Heating to a suitable temperature, holding long enough to reduce residual stresses, and cooling in air or as prescribed.

Annealing — Heating to a suitable temperature, holding, and cooling at a suitable rate for the purpose of obtaining minimum hardness or strength.

Solution-Treating — Heating to a suitable temperature, holding long enough to allow one or more constituents to enter into solid solution, and cooling rapidly enough to hold the constituents in solution.

Aging, Precipitation-Hardening — Heating to a suitable temperature and holding long enough to obtain hardening by the precipitation of a constituent from the solution-treated condition.

The actual temperatures, holding times, and heating and cooling rates used in these treatments vary from alloy to alloy and are described in the applicable specifications.

Table 6.1. Heat-Resistant Alloys Index

Section	Designation
6.2	**Iron-Chromium-Nickel-Base Alloys**
	A-286
6.2.1	N-155
6.2.2	
6.3	**Nickel-Base Alloys**
6.3.1	Hastelloy X
6.3.2	Inconel 600 (Inconel)
6.3.3	Inconel 625
6.3.4	Inconel 706
6.3.5	Inconel 718
6.3.6	Inconel X-750 (Inconel X)
6.3.7	René 41
6.3.8	Waspaloy
6.4	**Cobalt-Base Alloys**
6.4.1	L-605 (Haynes Alloy 25)
6.4.2	HS 188

6.1.1 MATERIAL PROPERTIES

6.1.1.1 *Mechanical Properties* — The mechanical properties of the heat-resistant alloys are affected by relatively minor variations in chemistry, processing, and heat treatment. Consequently, the mechanical properties shown for the various alloys in this chapter are intended to apply only to the alloy, form (shape), size (thickness), and heat treatment indicated. When statistical values are shown, these are intended to represent a fair cross section of all mill production within the indicated scope.

Strength Properties — Room-temperature strength properties for alloys in this chapter are based primarily on minimum tensile property requirements of material specifications. Values for nonspecification strength properties are derived. The variation of properties with temperature and other data or interest are presented in figures or tables, as appropriate.

The strength properties of the heat-resistant alloys generally decrease with increasing temperatures or increasing time at temperature. There are exceptions to this statement, particularly in the case of age-hardening alloys; these alloys may actually show an increase in strength with temperature or time, within a limited range, as a result of further aging. In most cases, however, this increase in strength is temporary and, furthermore, cannot usually be taken advantage of in service. For this reason, this increase in strength has been ignored in the preparation of elevated temperature curves as described in Chapter 9.

At cryogenic temperatures, the strength properties of the heat-resistant alloys are generally higher than at room temperature, provided some ductility is retained at the low temperatures. For additional information on mechanical properties at cryogenic temperatures, other references, such as the Cryogenic Materials Data Handbook (OTS PB 161093), should be consulted.

Ductility — Specified minimum ductility requirements are presented for these alloys in the room-temperature property tables. The variation in ductility with temperature is somewhat erratic for the heat-resistant alloys. Generally, ductility decreases with increasing temperature from room temperature up to about 1200 to 1400°F, where it reaches a minimum value, then it increases with higher temperatures. Prior creep exposure may also affect ductility adversely. Below room temperature, ductility decreases with decreasing temperature for some of these alloys.

Stress-Strain Relationships — The stress-strain relationships presented are typical curves prepared as described in Section 9.3.2.

Creep — Data covering the temperatures and times of exposure and the creep deformations of interest are included as typical information in individual material sections. These presentations may be in the form of creep stress-lifetime curves for various deformation criteria as specified in Chapter 9 or as creep nomographs.

Fatigue — Fatigue S/N curves for unnotched and notched specimens at room temperature and elevated temperatures are shown in each alloy section. Fatigue crack propagation data are also presented.

6.1.1.2 *Physical Properties* —Selected physical-property data are presented for these alloys. Processing variables and heat treatment have only a slight effect on these values; thus, the properties listed are applicable to all forms and heat treatments.

CHAPTER 7

MISCELLANEOUS ALLOYS AND HYBRID MATERIALS

7.1 GENERAL

This chapter contains the engineering properties and related characteristics of miscellaneous alloys and hybrid materials. In addition to the usual properties, some characteristics relating to the special uses of these alloys are described. For example, the electrical conductivity is reported for the bronzes and information is included on toxicity of particles of beryllium and its compounds, such as beryllium oxide.

The organization of this chapter is in sections by base metal and subdivided as shown in Table 7.1.

Table 7.1. Miscellaneous Alloys Index

Section	Designation
7.2	**Beryllium**
7.2.1	Standard Grade Beryllium
7.3	**Copper and Copper Alloys**
7.3.1	Manganese Bronzes
7.3.2	Copper Beryllium
7.4	**Multiphase Alloys**
7.4.1	MP35N Alloy
7.4.2	MP159 Alloy
7.5	**Aluminum Alloy Sheet Laminates**
7.5.1	2024-T3 Aramid Fiber Reinforced Sheet Laminate
7.5.2	7475-T761 Aramid Fiber Reinforced Sheet Laminate

7.2 BERYLLIUM

7.2.0 GENERAL

This section contains the engineering properties and related characteristics of beryllium used in aerospace structural applications. Beryllium is a lightweight, high modulus, moderate temperature capability metal that is used for specific aerospace applications. Structural designs utilizing beryllium sheet should allow for anisotropy, particularly the very low short transverse properties. Additional information on the fabrication of beryllium may be found in References 7.2.0(a) through (i).

7.2.1 STANDARD GRADE BERYLLIUM

7.2.1.0 ***Comments and Properties*** — Standard grade beryllium bars, rods, tubing, and machined shapes are produced from vacuum hot-pressed powder with 1½ percent maximum beryllium oxide content. These products are also available in numerous other compositions for special purposes but are not covered in this document. Sheet and plate are fabricated from vacuum hot-pressed powder with 2 percent maximum beryllium oxide content.

CHAPTER 8

STRUCTURAL JOINTS

This chapter, while comprising three major sections, primarily is concerned with joint allowables. Section 8.1 is concerned with mechanically fastened joints; Section 8.2, with metallurgical joints (various welding and brazing processes). Section 8.3 contains information for structural component data; it is concerned with bearings, pulleys, and cables.

With particular reference to Section 8.1, the introductory section (8.1.1) contains fastener indexes that can be used as a quick reference to locate a specific table of joint allowables. Following this introductory section are five sections comprising the five major fastener categories, as shown in Table 8.0.1.

Table 8.0.1. Structural Joints Index (Fastener Type)

Section	Fastener Type
8.1.2	Solid Rivets
8.1.2.1	Protruding head
8.1.2.2	Flush head
8.1.3	Blind fasteners
8.1.3.1	Protruding head
8.1.3.2	Flush head
8.1.4	Swaged collar fasteners
8.1.4.1	Protruding head
8.1.4.2	Flush head
8.1.5	Threaded fasteners
8.1.5.1	Protruding head
8.1.5.2	Flush head
8.1.6	Special fasteners
8.1.6.1	Fastener sleeves

In each of the five major sections, there are subsections that describe the factors to be considered in determining the strength of fasteners and joints. After each major section, pertinent tables are presented.

Similarly, Section 8.2 has an introductory section (8.2.1), followed by two major sections comprising different metallurgical joints as shown in Table 8.0.2.

Table 8.0.2. Structural Joints Index (Joining Methods)

Section	Joining Methods
8.2.2	Welded joints
8.2.2.1	Fusion
8.2.2.2	Flush and pressure
8.2.2.3	Spot and seam
8.2.3	Brazing
8.2.3.1	Copper
8.2.3.2	Silver

Following each 4-digit section, applicable tables and figures for the particular section are presented.

8.1 MECHANICALLY FASTENED JOINTS

To determine the strength of mechanically fastened joints, it is necessary to know the strength of the individual fasteners (both by itself, and when installed in various thicknesses of the various materials). In most cases, failures in such joints occur by tensile failure of the fasteners, shearing of the fasteners and by bearing and/or tearing of the sheet or plate.

8.1.1 INTRODUCTION AND FASTENER INDEXES — Five categories of mechanical fasteners are presently contained in this Handbook, generically defined as follows:

Solid Rivets — Solid rivets are defined as one piece fasteners installed by mechanically upsetting one end.

Blind Fasteners — Blind fasteners are usually multiple piece devices that can be installed in a joint which is accessible from one side only. When a blind fastener is being installed, a self-contained mechanical, chemical, or other feature forms an upset on its inaccessible or blind side. These fasteners must be destroyed to be removed. This fastener category includes such fasteners as blind rivets, blind bolts, etc.

Swaged Collar Fasteners — Swaged collar fasteners are multiple piece fasteners, usually consisting of a solid pin and a malleable collar which is swaged or formed onto the pin to clamp the joint. This fastener usually is permanently installed. This fastener class includes such fasteners as "Hi-Shear" rivets, "Lockbolts", and "Cherrybucks".

Threaded Fasteners — Fasteners in this category are considered to be any threaded part (or parts) that after assembly in a joint can be easily removed without damage to the fastener or to the material being joined. This classification includes bolts, screws, and a wide assortment of proprietary fasteners.

Special Fasteners — As the name implies, this category of fastener is less commonly used in primary aircraft structure than the four categories listed above. Examples of such fastening systems are sleeves, inserts, panel fasteners, etc.

In the following 3-digit sections, descriptive information is presented relative to the establishment of design allowables in joints containing these four categories of fasteners. Following each such section are the various tables of joint allowables or associated information for computing joint allowables as described.

Tables 8.1.1(a) through (e) are fastener indexes that list the joint allowables tables for each fastener category. These indexes are provided to make it easier to locate the allowables table for a given fastener and sheet material combination. Each of the indexes generally is similarly structured in the following manner. The left-hand column describes the fastener by referring to the MS or NAS part number or to a vendor part number when the fastener is not covered by either series. The second column contains the table number for the allowables table for each fastener. The fastener column has been so arranged that when protruding head and countersunk head fasteners are included in a given fastener index table, the protruding head tables appear first in the second column. The third column identifies generally the base material of the fastener. Generic terms usually are used, such as steel, aluminum, titanium, etc. The fourth column identifies the specific sheet or plate material.

It is recommended that Section 9.4.1 be reviewed in its entirety since it contains detailed information on the generation and analysis of joint data that results in the joint allowables tables contained in this section.

8.1.1.1 ***Fastener Shear Strengths*** — Fastener shear strengths accepted and documented by the aerospace industry and government agencies are listed in Table 8.1.1.1. Some existing tables in MIL-HDBK-5 may reflect other values; however, new fastener proposals will be classified in accordance with the above-noted table.

8.1.1.2 ***Edge Distance Requirements*** — The joint allowables in MIL-HDBK-5 are based on joint tests having edge distances of twice the nominal hole diameter, 2D. Therefore, the allowables are applicable only to joints having 2D edge distance.

Table 8.1.1(a). Fastener Index for Solid Rivets

Fastener Identification[a]	Table Number	Rivet Material	Sheet Material	Page No.
Rivet Hole Size	8.1.2(a)	...	...	8-10
Shear Strength of Solid Rivets	8.1.2(b)	...	...	8-11
Unit Bearing Strength	8.1.2.1(a)	...	...	8-12
Shear Strength Corection Factors	8.1.2.1(b)	Aluminum	...	8-13
NAS1198 (MC)[b]	8.1.2.1(c)	A-286	A-286	8-14
MS20427M (MC)	8.1.2.2(a)	Monel	AISI 301/302	8-15
MS20427M (D)[b]	8.1.2.2(b)	Monel	AISI 301/302	8-16
MS20426AD (D)	8.1.2.2(c)	Aluminum	Aluminum	8-17
MS20426D (D)	8.1.2.2(d)	Aluminum	Aluminum	8-18
MS20426DD (D)	8.1.2.2(e)	Aluminum	Aluminum	8-19
MS20426 (MC)	8.1.2.2(f)	Aluminum	Clad 2024-T42	8-20
MS20426B (MC)	8.1.2.2(g)	Aluminum	AZ31B-H24	8-21
MS20427M (MC)	8.1.2.2(h)	Monel	Com Pure Titanium	8-22
BRFS-D (MC)	8.1.2.2(i)	Aluminum	Clad 2024-T3	8-23
BRFS-AD (MC)	8.1.2.2(j)	Aluminum	Clad 2024-T3	8-24
BRFS-DD (MC)	8.1.2.2(k)	Aluminum	Clad 2024-T3	8-25
BRFS-T (MC)	8.1.2.2(l)	Ti-45Cb	Clad 7075-T6/Ti-6Al-4V	8-26
MS14218E	8.1.2.2(m)	Aluminum	Clad 2024-T3	8-27
NAS1097E (MC)	8.1.2.2(n)	Aluminum	Clad 2024-T3/7075-T6	8-28
MS14218AD (MC)	8.1.2.2(o)	Aluminum	Clad 2024-T3	8-29
MS14219E (MC)	8.1.2.2(p)	Aluminum	Clad 2024-T3	8-30
MS14219E (MC)	8.1.2.2(q)	Aluminum	Clad 7075-T6	8-31
MS20426E	8.1.2.2(r)	Aluminum	Clad 2024-T3	8-32
MS20426E	8.1.2.2(s)	Aluminum	Clad 7075-T3	8-33

a In some cases, entries in this table identify the subject matter in certain tables.
b MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(b). Fastener Index for Blind Fasteners

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
Protruding-head, Friction-Lock Blind Rivets				
CR 6636	8.1.3.1.1(a)	A-286	Various	8-35
MS20600M	8.1.3.1.1(b)	Monel	AISI 301	8-36
MS20600M	8.1.3.1.1(c)	Monel	Clad 2024-T3/7075-T6	8-37
MS20600AD and MS20602AD	8.1.3.1.1(d)	Aluminum	Clad 2024-T3	8-38
MS20600B	8.1.3.1.1(e)	Aluminum	AZ31B-H24	8-39
Protruding-head, Mechanical-Lock Blind Rivets				
NAS1398C	8.1.3.1.2(a)	A-286	Alloy Steel	8-40
CR 2643	8.1.3.1.2(a)	A-286	Alloy Steel	8-40
NAS1398 MS or MW	8.1.3.1.2(b)	Monel	AISI 301-½ Hard	8-41
NAS1398 MS or MW	8.1.3.1.2(c)	Monel	Clad 7075-T6	8-42
NAS1398B	8.1.3.1.2(d_1)	Aluminum	Clad 2024-T3	8-43
NAS1398D	8.1.3.1.2(d_1)	Aluminum	Clad 2024-T3	8-43
NAS1738B and NAS1738E	8.1.3.1.2(d_2)	Aluminum	Clad 2024-T3	8-44
NAS1398B	8.1.3.1.2(e)	Aluminum	AZ31B-H24	8-45
NAS1738B and NAS1738E	8.1.3.1.2(e)	Aluminum	AZ31B-H24	8-45
CR 2A63	8.1.3.1.2(f)	Aluminum	Clad 2024-T81	8-46
CR 4623	8.1.3.1.2(g)	A-286	Clad 7075-T6	8-47
CR 4523	8.1.3.1.2(h)	Monel	Clad 7075-T6	8-48
NAS1720KE and NAS1720KE (L)	8.1.3.1.2(i)	Aluminum	Clad 7075-T6	8-49
NAS1720C and NAS1720C (L)	8.1.3.1.2(j)	A-286	Clad 2024-T3	8-50
M7885/2	8.1.3.1.2(k)	Aluminum	Clad 7075-T6	8-51
M7885/6	8.1.3.1.2(l)	Aluminum	Clad 2024-T3	8-52
AF3243	8.1.3.1.2(m)	Aluminum	Clad 2024-T3	8-53
HC3213	8.1.3.1.2(n)	Aluminum	Clad 2024-T3	8-54
HC6223	8.1.3.1.2(o)	Aluminum	Clad 2024-T3	8-55
HC6253	8.1.3.1.2(p)	Aluminum	Clad 2024-T3	8-56
Flush-head, Friction-Lock Blind Rivets				
CR 6626 (MC)[a]	8.1.3.2.1(a)	A-286	Various	8-57
MS20601M (MC)	8.1.3.2.1(b)	Monel	17-7PH (TH1050)	8-58
MS20601M (D)[a]	8.1.3.2.1(c)	Monel	AISI 301	8-59
MS20601M (MC)	8.1.3.2.1(d_1)	Monel	AISI 301-Ann	8-60
MS20601M (MC)	8.1.3.2.1(d_2)	Monel	AISI 301-¼ Hard	8-61
MS20601M (MC)	8.1.3.2.1(d_3)	Monel	AISI 301-½ Hard	8-62
MS20601M (MC)	8.1.3.2.1(e)	Monel	7075-T6	8-63
MS20601AD and MS20603AD (MC)	8.1.3.2.1(f)	Aluminum	Clad 2024-T3	8-64
MS20601B (MC)	8.1.3.2.1(g)	Aluminum	AZ31B-H24	8-65

a MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(b). Fastener Index for Blind Fasteners—Continued

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
		Flush-head, Mechanical-Lock Spindle Blind Rivets		
NAS1399C (MC)	8.1.3.2.2(a)	A-286	Alloy Steel	8-66
CR 2642 (MC)	8.1.3.2.2(a)	A-286	Alloy Steel	8-66
NAS1399 MS or MW (MC)	8.1.3.2.2(b)	Monel	AISI 301-½ Hard	8-67
NAS1291C (MC)	8.1.3.2.2(c)	A-286	Clad 7075-T6	8-68
NAS1399 MS or MW (MC)	8.1.3.2.2(d)	Monel	Clad 7075-T6	8-69
NAS1921M (MC)	8.1.3.2.2(e)	Monel	Clad 7075-T6	8-70
CR 2A62 (MC)	8.1.3.2.2(f)	Aluminum	Clad 2024-T81	8-71
NAS1921B (MC)	8.1.3.2.2(g)	Aluminum	Clad 7075-T6	8-72
NAS1399B (MC)	8.1.3.2.2(h)	Aluminum	Clad 2024-T3	8-73
NAS1399D (MC)	8.1.3.2.2(h)	Aluminum	Clad 2024-T3	8-73
NAS1739B and NAS1379E (MC)	8.1.3.2.2(i)	Aluminum	Clad 2024-T3	8-74
NAS1739B and NAS1739E (D)	8.1.3.2.2(i)	Aluminum	Clad 2024-T3	8-74
NAS1399B (MC)	8.1.3.2.2(j)	Aluminum	AZ31B-H24	8-75
NAS1739B and NAS1739E (MC)	8.1.3.2.2(j)	Aluminum	AZ31B-H24	8-75
CR 4622 (MC)	8.1.3.2.2(k)	A-286	Clad 7075-T6	8-76
CR 4522 (MC)	8.1.3.2.2(l)	Monel	Clad 7075-T6/T651	8-77
NAS1721KE and NAS1721KE (L) (MC)	8.1.3.2.2(m)	Aluminum	Clad 2024-T3	8-78
NAS1721C and NAS1721C (L) (MC)	8.1.3.2.2(n)	A-286	Clad 7075-T6	8-79
M 7885/3 (MC)	8.1.3.2.2(o)	Aluminum	Clad 2024-T3	8-80
M 7885/7 (MC)	8.1.3.2.2(p)	Aluminum	Clad 2024-T3	8-81
HC3212 (MC)	8.1.3.2.2(q)	Aluminum	Clad 2024-T3	8-82
MBC 4807 and MBC 4907	8.1.3.2.2(r)	Aluminum	Clad 2024-T3	8-83
MBC 4801 and MBC 4901	8.1.3.2.2(s)	Aluminum	Clad 2024-T3	8-84
HC6222	8.1.3.2.2(t)	Aluminum	Clad 2024-T3	8-85
HC6252	8.1.3.2.2(u)	Aluminum	Clad 2024-T3	8-86
		Flush-head Blind Bolts		
MS21140 (MC)	8.1.3.2.3(a)	A-286	Clad 7075-T6/T651	8-87
MS90353 (MC)	8.1.3.2.3(b_1)	Alloy Steel	Clad 2024-T3/T351	8-88
MS90353 (MC)	8.1.3.2.3(b_2)	Alloy Steel	Clad or Bare 7075-T6 or T651	8-89
FF-200, FF-260 and FF-312 (MC)	8.1.3.2.3(c)	Alloy Steel	Clad 2024-T42/ 7075-T6	8-90
NS 100 (MC)	8.1.3.2.3(d)	Alloy Steel	Clad 7075-T6	8-91
SSHFA-200 and SSHFA-260(MC)	8.1.3.2.3(e)	Aluminum	Clad 2024-T42/ 7075-T6	8-92
PLT-150 (MC)	8.1.3.2.3(f)	Alloy Steel	Clad 7075-T6/T651	8-93
NAS1670L (MC)	8.1.3.2.3(g)	Alloy Steel	Clad 7075-T6/T651	8-94
NAS1674L (MC)	8.1.3.2.3(h)	Aluminum	Clad 7075-T6	8-95

a MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(c). Fastener Index for Swaged-Collar/Upset-Pin Fasteners

Fastener Identification	Table Number	Fastener Pin Material	Sheet or Plate Material	Page No.
Ultimate Single-Shear and Tensile Strengths	8.1.4	Alloy Steel and Alum.	...	8-98
CSR 925	8.1.4.1(a)	Titanium	Clad 7075-T6	8-99
CSR 925	8.1.4.1(b)	Titanium	Clad 2024-T3	8-100
NAS1436-NAS1442 (MC)[a]	8.1.4.2(a)	Alloy Steel	Clad 7075-T6/T651	8-101
NAS7024-NAS7032 (MC)	8.1.4.2(b)	Alloy Steel	Clad 7075-T6/T651	8-102
CSR 924 (MC)	8.1.4.2(c)	Titanium	Clad 7075-T6	8-103
CSR 924 (MC)	8.1.4.2(d)	Titanium	Clad 2024-T3	8-104
HSR 201 (MC)	8.1.4.2(e)	A-286	Clad 7075-T6	8-105
HSR 101 (MC)	8.1.4.2(f)	Titanium	Clad 7075-T6	8-106
GPL 3SC-V (MC)	8.1.4.2(g)	Titanium	Clad 7075-T6	8-107
GPL 3SC-V (MC)	8.1.4.2(h)	Titanium	Clad 2024-T3	8-108
LGPL 2SC-V (MC)	8.1.4.2(i)	Titanium	Clad 7075-T6	8-109
LGPL 2SC-V (MC)	8.1.4.2(j)	Titanium	Clad 2024-T3	8-110

a MC, machine countersunk holes.

Table 8.1.1(d). Fastener Index for Threaded Fasteners

Fastener Identification[a]	Table Number	Fastener Sleeve Material	Sheet	Page No.
Single Shear Strength	8.1.5(a)	Steel	...	8-113
Tensile Strength	8.1.5(b_1)	Steel	...	8-114
Tensile Strength	8.1.5(b_2)	...	...	8-115
Unit Bearing Strength	8.1.5.1	Alloy Steel	...	8-116
AN 509 Screws (MC)[b]	8.1.5.2(a_1)	Alloy Steel	Clad 2024-T3	8-117
AN 509 Screws (MC)	8.1.5.2(a_2)	CRES	Clad 7075-T6	8-118
PBF 11 (MC)	8.1.5.2(b)	Alloy Steel	Ti-6Al-4V	8-119
TL 100 (MC)	8.1.5.2(c)		Clad 7075-T6	8-120
TLV 100 (MC)	8.1.5.2(d)	Titanium	Clad 7075-T6	8-121
HPB-V (MC)	8.1.5.2(e)	Titanium	Clad 7075-T6	8-122
KLBHV with KFN 600 (MC)	8.1.5.2(f)	Titanium	Clad 7075-T6	8-123
HL-61-70 (MC)	8.1.5.2(g)	CRES	Clad 7075-T6	8-124
HL-719-79 (MC)	8.1.5.2(h)	Alloy Steel	Clad 7075-T6	8-125
HL-11 (MC)	8.1.5.2(i)	Titanium	Clad 7075-T6	8-126
HL-911 (MC)	8.1.5.2(j)	Titanium	Clad 7075-T6	8-127
NAS4452S and KS 100-FV with NAS4445DD (MC)	8.1.5.2(k)	Alloy Steel or Titanium	Clad 7075-T6	8-128
HPG-V (MC)	8.1.5.2(l)	Titanium	Clad 7075-T6	8-129
NAS4452V with NAS4445 DD (MC)	8.1.5.2(m)	Titanium	Clad 7075-T6	8-130
HL18Pin, HL70 Collar (MC)	8.1.5.2(n)	Alloy Steel	Clad 7075-T6	8-131
HL19 Pin, HL70 Collar (MC)	8.1.5.2(o)	Alloy Steel	Clad 7075-T6	8-132

a In some cases entries in this table identify the subject matter in certain tables.
b MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(e). Fastener Index for Special Fasteners

Fastener Identification	Table Number	Fastener Pin Material	Sheet or Plate Material	Page No.
ACRES Sleeves	...	A-286	Clad 7075-T6	8-133
MIL-B-8831/4 (MC)[a]	8.1.6.2(a)	Steel Pin, Aluminum Sleeve	Clad 7075-T6	8-134
MIL-B-8831/4 (MC)	8.1.6.2(b)	Steel Pin, Aluminum Sleeve	Clad 2024-T3	8-135

a MC, machine countersunk holes.

Table 8.1.1.1. Fastener Shear Strengths

F_{su}, ksi	Examples of Current Alloys Which Meet Level[a]	Current Usage: Driven Rivets	Current Usage: Blind Fasteners	Current Usage: Solid Shank Fasteners
28	5056	X	X	
30	2117	X	X	
34	2017	X	X	
36	2219	X	X	
38	2017	X	X	
41	2024 and 7050-T73	X		
43	7050-T731	X	X	X
46	7075		X	
49	Monel	Undriven		
50	Ti/Cb	X		
55	Monel		X	
75	Alloy Steel and CRES		X	X
78	A-286			X
90	A-286	Undriven		
95	Alloy Steel, A-286, Ti-6Al-4V	X	X	X
108	Alloy Steel and Ti-6Al-2Sn			X
110	A-286			X
112	Alloy Steel		X	X
125	Alloy Steel and CRES			X
132	Alloy Steel			X
145	MP35N			X
156	Alloy Steel			X
180	Alloy Steel			X

a Different tempers and thermal treatments are used to obtain desired fastener shear strengths.

CHAPTER 9

GUIDELINES FOR THE PRESENTATION OF DATA

This chapter contains Guidelines for judging adequacy of data, procedures for analyzing data in determining property values for inclusion in previous chapters, and formats for submitting results of analyses to the MIL-HDBK-5 Coordination Group for approval.

The following subindex should be helpful in locating sections of these Guidelines applicable to various properties:

9.0 SUMMARY

The objective of this summary is to provide a global overview of Chapter 9 without defining specific statistical details. This overview will be most helpful to those unfamiliar with the statistical procedures used in MIL-HDBK-5 and to those who would like to learn more about the philosophy behind the MIL-HDBK-5 guidelines.

Chapter 9 is the “rule book” for MIL-HDBK-5. Since 1966, these guidelines have described statistical procedures used to calculate mechanical properties for alloys included in the Handbook. Recommended changes in the guidelines are reviewed first by the Guidelines and Emerging Materials Task Group (GEMTG) and later approved by the entire coordination committee. Recommended changes in statistical procedures within the guidelines are evaluated first by the Statistics Working Group (SWG), which supports the GEMTG. Similarly, recommended changes in fastener analysis procedures are examined by the Fastener Task Group (FTG) before approval by the coordination committee.

Chapter 9 is divided into 6 subchapters which cover the analysis methods used to define room and elevated temperature properties. The room temperature mechanical properties are tensile, compression, bearing, shear, fatigue, fracture toughness, elongation and elastic modulus. The elevated temperature properties are the same, except that creep and stress rupture properties are added to the list. Analysis procedures for fatigue, fatigue crack growth and mechanically fastened joints are also covered since these data are commonly used in aircraft design. The presentation of these data varies depending upon the data type. For instance, the room temperature mechanical properties (tensile, compression, bearing, shear, elongation and elastic modulus) are provided in a tabular format, while the fatigue, elevated temperature properties, and typical stress-strain curves are presented in graphical format.

Before an alloy can be considered for inclusion in MIL-HDBK-5, it must be covered by a commercial or government specification. There are two main reasons for this: (1) the alloy, and its method of manufacture, must be “reduced to standard practice” to increase confidence that the material, if obtained from different suppliers, will still demonstrate similar mechanical properties, and (2) specification minimum properties are included in MIL-HDBK-5 tables as design properties in situations where there are insufficient data to determine statistically based material design values.

The majority, by far, of the data in MIL-HDBK-5 are room temperature design properties: including tensile (F_{tu}, F_{ty}), shear (F_{su}), compression (F_{cy}), bearing strengths (F_{bru} and F_{bry}), elongation and elastic modulus. Room temperature design properties are the primary focus in the Handbook because most aircraft, commercial and military, typically operate at near-ambient temperatures and because most material specifications include only room temperature property requirements.

Design minimum mechanical properties tabulated in MIL-HDBK-5 are calculated either by “direct” or “indirect” statistical procedures. The minimum sample size required for the direct computation of T_{99} and T_{90} values (from which A and B-basis design properties are established) is 100. These 100 observations must include data from at least 10 heats and lots (as defined in the next paragraph). A T_{99} value is a statistically computed, one-sided lower tolerance limit, representing a 95 percent confidence lower limit on the first percentile of the distribution. Similarly, a T_{90} value is a statistically computed, one-sided lower tolerance limit, representing a 95 percent lower confidence limit on the tenth percentile of the distribution. If the sample cannot be described by a normal or Weibull distribution, the T_{99} and T_{90} values must be computed by nonparametric (distribution free) means, which can only be done if there are at least 299 observations. In most cases, only minimum tensile ultimate and yield strength values are determined by the direct method. T_{90} values are not computed if there are insufficient data to compute T_{99} values, even though a much smaller sample size is required to compute nonparametric T_{90} values. This is because the general consensus within the MIL-HDBK-5 committee has been that a large number of observations (in the realm of 100) are needed from a large number of heats and lots (e.g. 10) for a particular material to properly characterize the variability in strength of that product.

A lot represents all of the material of a specific chemical composition, heat treat condition or temper, and product form that has passed through all processing operations at the same time. Multiple lots can be obtained from a single heat. A heat of material, in the case of batch melting, is all of the material that is cast at the same time from the same furnace and is identified with the same heat number. In the case of continuous melting, a single heat of material is generally poured without interruption. The exception is for ingot metallurgy wrought aluminum products, where a single heat is commonly cast in sequential aluminum ingots, which are melted from a single furnace change and poured in one or more drops without changes in the processing parameters (see Table 9.1.6.2).

Minimum compression, bearing, and shear strengths are typically determined through the indirect method. This is done to reduce cost, because as few as 10 data points (from 2 heats and 10 lots) can be used, in combination with "paired" direct properties to compute a design minimum value. In this indirect method, the compression, bearing, and shear strengths are paired with tensile values determined in the same region of the product to produce a ratio. Statistical analyses of these ratios are conducted to obtain lower bound estimates of the relationship between the primary property and the ratioed property. These ratios are then multiplied with the appropriate F_{tu} or F_{ty} in the Handbook to obtain the F_{su}, F_{cy}, F_{bru}, F_{bry} values for shear, compression, and bearing (ultimate and yield), respectively.

Many mechanical property tables in the Handbook include data for specific grain directions and thickness ranges. This is done to better represent anisotropic materials, such as wrought products, that often display variations in mechanical properties as a function of grain direction and/or product thickness. Therefore, it is common practice to test for variability in mechanical properties as a function of product thickness. This is done through the use of regression analysis for both direct and indirect properties. If a regression is found to be significant, properties may be computed separately (without regression) for reduced thickness ranges.

To compliment the mechanical property tables, the Handbook also contains typical stress-strain curves. These curves are included to illustrate each material's yield behavior and to graphically display differences in yield behavior for different grain directions, tempers, etc. These curves are identified as typical because they are based upon only a few test points. Typical curves are shown for both tension and compression and are extended to just beyond the 0.2 percent yield stress. Each typical curve also contains a shape factor called the Ramberg-Osgood number (n). These numbers can be used in conjunction with a material's elastic modulus to empirically develop a stress-strain curve. Typical tensile full-range stress-strain curves are also provided that illustrate deformation behavior from the proportional limit to fracture. In addition, compression tangent-modulus curves are provided to describe compression instability.

Effect of temperature and thermal exposure curves are included throughout the Handbook. For tensile properties, the curves are presented as a percentage of the room temperature design value. For these curves, there is a minimum data requirement and statistical procedures have been established to construct the curves. The creep rupture plots are shown as typical isothermal curves of stress versus time. The physical properties are shown as a function of temperature for each property, i.e., specific heat, thermal conductivity, etc. Physical properties are reported as average actual values, not a percentage of a room temperature value.

In addition to the mechanical properties, statistically based S/N fatigue curves are provided in the Handbook, since many airframe structures experience dynamic loading conditions. The statistical procedures are fairly rigorous. For example, the procedure describes how to treat outliers and run-outs (discontinued tests), and which models to use to best-fit a specific set of data. Each fatigue figure includes relevant information such as K_t, R value, material properties, sample size and equivalent stress equation. Each figure should be closely examined by the user to properly identify the fatigue curves required for a particular design.

Design properties for mechanical fasteners and mechanically fastened elements are also included in MIL-HDBK-5. A unique analysis procedure has been developed for mechanical fasteners because fasteners generally do not develop the full bearing strength of materials in which they are installed. Realistic joint allowables are determined from test data using the statistical analysis procedures described in Chapter 9. There are four different types of fasteners for which design allowables must be determined, as described in Section 4.

The last section in the Handbook (Section 6) provides a detailed description of statistical procedures used in Chapter 9 for the analysis of data. Most of these procedures are backed up with examples and appropriate statistical tables.

9.1 GENERAL

This section of the Guidelines covers general information. Information specific to individual properties can be found in pertinent sections.

9.1.1 INTRODUCTION — Design properties in MIL-HDBK-5 are used in the design of aerospace structures and elements. Thus, it is exceedingly important that the values presented in MIL-HDBK-5 reflect as accurately as possible the actual properties of the products covered.

Throughout the Guidelines, many types of statistical computations are referenced. Since these may not be familiar to all who may be analyzing data in the preparation of MIL-HDBK-5 proposals, a detailed description of each operation is required. To present the detailed description in the individual sections, however, would unnecessarily complicate the orderly presentation of the overall computational procedures. Therefore, the detailed description of the statistical techniques have been covered in Section 9.6.

9.1.2 APPLICABILITY — Minimum data requirements and analytical procedures defined in these Guidelines for establishment of MIL-HDBK-5 design properties and elevated temperature curves for these properties should be used to obtain approval of such values or curves when proposed to the MIL-HDBK-5 Coordination Group or a certifying agency. However, the minimum data requirements and analytical procedures are not mandatory; to the extent of precluding use of other analytical procedures which can be substantiated. Any exceptions or deviations must be reported when requesting approval of these values or curves by the Coordination Group or certifying agency.

9.1.3 APPROVAL PROCEDURES — The MIL-HDBK-5 Coordination Group (a voluntary, joint Government-Industry activity) meets twice yearly. At each meeting, this group acts upon proposed changes or additions to the document submitted in writing in advance of the meeting. The agenda is normally mailed to attendees four weeks prior to the meeting date, and the minutes four weeks following the meeting. Attachments for either the agenda or the minutes should be delivered to the Secretariat well in advance of the mailing date.

Attachments containing proposed changes or additions to the document shall include specific notations of changes or additions to be made; adequate documentation of supporting data; analytical procedures used (see Section 9.1.4); discussion of analysis of data; and a listing of exceptions or deviations from the requirements of these Guidelines.

Approval procedures for establishment of MIL-HDBK-5 equivalent design values are defined by the individual certifying agency.

9.1.4 DOCUMENTATION REQUIREMENTS — The purpose of adequate documentation of proposals submitted to the MIL-HDBK-5 Coordination Group is to permit an independent evaluation of proposals by each interested attendee and to provide a historical record of actions of the Coordination Group. For this reason, both supporting data and a description of analytical procedures employed must be made available to attendees, either as an integral portion of an attachment to the agenda or minutes, or by reference to other documents that may reasonably be expected to be in the possession of MIL-HDBK-5 Meeting attendees. A specific example of the latter would be certain reports of Government-sponsored research or material evaluations for which distribution included the MIL-HDBK-5 attendance list. In some cases involving large quantities of supporting data, it may suffice (at the discretion of the Coordination Group) to furnish a single copy of these data to the Secretariat, from whom they would be available to interested attendees.

9.1.5 SYMBOLS AND DEFINITIONS (also see Sections 9.2.2, 9.3.4.2, 9.3.6.2, 9.4.1.2, 9.5.1.2, and 9.6) —

α	—	Significance level; probability (risk) of erroneously rejecting the null hypothesis (see Section 9.6.2).
$\alpha_{99,90}$	—	Shape parameter estimates for a T_{99} or T_{90} tolerance bound based on an assumed three-parameter Weibull distribution.
α_{50}	—	Shape parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
A	—	A-basis for mechanical property (see Section 9.2.2.1).
AD	—	Anderson-Darling test statistic, computed in goodness-of-fit tests for normality or Weibullness.
$\beta_{99,90}$	—	Scale parameter estimate for a T_{99} or T_{90} tolerance bound based on an assumed three-parameter Weibull distribution.
β_{50}	—	Scale parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
B	—	B-basis for mechanical property (see Section 9.2.2.1).
df	—	Degrees of freedom.
F	—	The ratio of two sample variances.
heat	—	All material identifiable to a single molten metal source. (All material from a heat is considered to have the same composition. A heat may yield one or more ingots. A heat may be divided into several lots by subsequent processing.)
$k_{99,90}$	—	The T_{99} or T_{90} tolerance limit factor for the normal distribution, based on 95 percent confidence and a sample of size n.
log	—	Base 10 logarithm.
lot	—	All material from a heat or single molten metal source of the same product type having the same thickness or configuration, and fabricated as a unit under the same conditions. If the material is heat treated, a lot is the above material processed through the required heat-treating operations as a unit.
ln	—	Natural (base e) logarithm.
n	—	Number of individual measurements or pairs of measurements; Ramberg-Osgood parameter.
r	—	Ratio of two paired measurements; rank of test point within a sample.
$\bar{r}$	—	Average ratio of paired measurements.
S	—	S-basis for mechanical property values (see Section 9.2.2.1).
s	—	Estimated population standard deviation.
$\tau_{99,90}$	—	Threshold estimates for a T_{99} or T_{90} tolerance bound based on an assumed three-parameter Weibull distribution.
τ_{50}	—	Threshold estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
t	—	Tolerance factor for the "t" distribution with the specified "confidence" and appropriate degrees of freedom.
T_{90}	—	Statistically based lower tolerance bound for a mechanical property such that at least 90 percent of the population is expected to exceed T_{90} with 95 percent confidence.
T_{99}	—	Statistically based lower tolerance bound for a mechanical property such that at least 99 percent of the population is expected to exceed T_{99} with 95 percent confidence.
$V_{99,90}$	—	The T_{99} or T_{90} tolerance limit factor for the three-parameter Weibull distribution, based on 95 percent confidence, a sample of size n, and a specified degree of upper tail censoring.
X_i	—	Value of an individual measurement.
$\bar{X}$	—	Average value of individual measurements.
Σ	—	The sum of.
$'$	—	Value determined by regression analysis.

9.1.6 DATA REQUIREMENTS FOR INCORPORATION OF A NEW PRODUCT INTO MIL-HDBK-5 — This section specifies requirements for the incorporation of a new product into MIL-HDBK-5 on an S-basis (see Section 9.2.2.1 for definition). These requirements are applicable to each alloy, product form, and heat treat condition or temper. Sections 9.1.6.2 through 9.1.6.7 delineate requirements for a test program for the determination of mechanical property data suitable for computation of derived properties (see Section 9.2.10). A test matrix, based on these requirements, is shown in Table 9.1.6.

9.1.6.1 *Material Specification* — To be considered for inclusion in MIL-HDBK-5, a product must be covered by an industry specification (AMS specification issued by SAE Aerospace Materials Division or an ASTM standard published by the American Society for Testing and Materials), or a government specification (Military or Federal). If a public specification for the product is not available, action should be initiated to prepare a draft specification. Standard manufacturing procedures shall have been established for the fabrication and processing of production material before a draft specification is prepared. The draft specification shall describe a product which is commercially available on a production basis. An AMS draft specification should be submitted to the SAE Aerospace Materials Division and an ASTM standard should be transmitted to the American Society for Testing and Materials for publication. See Section 9.1.6.8 for requirements to substantiate the S-basis properties.

9.1.6.2 *Material* — The product used for the determination of mechanical properties suitable for use in the determination of minimum design (derived) values for incorporation into MIL-HDBK-5 shall be production material. The material shall have been produced using production facilities and standard fabrication and processing procedures. If a test program to determine requisite mechanical properties is initiated before a public specification describing this product is available, precautionary measures shall be taken to ensure that the product supplied for the test program conforms to the specification, when published, and represents production material.

Ten lots of material from at least two production heats, casts or melts for each product form and heat treat condition shall be tested to determine required mechanical properties. See Table 9.1.6.2 for definitions of heat, cast, and melt. A lot is defined as all material of a specific chemical composition, heat treat condition or temper, and product form which has been processed at the same time through all processing operations. Different sizes and configurations from a heat cast or melt shall be considered different lots. For a single lot of material, only one heat treat lot may be used to meet the ten-lot requirement. Thicknesses of the 10 lots to be tested shall span the thickness range of the product form covered by the material specification (or for the thickness range for which design values are to be established).

Dimensionally discrepant castings or special test configurations may be used for the development of derived properties with prior approval by the MIL-HDBK-5 Coordination Group, providing these castings meet the requirements of the applicable material specification. Design values for separately cast test specimens shall not be presented in MIL-HDBK-5.

9.1.6.3 *Test Specimens* — Mechanical property ratios are utilized in the analysis of data to determine minimum design values. Tensile yield in other than primary test direction, compressive yield, and bearing yield strengths are paired with the tensile yield strength in the primary test direction for each lot. Tensile ultimate in other than the primary test direction, shear ultimate, and bearing ultimate strengths are paired with the tensile ultimate strength in the primary test direction. See Table 9.2.10 for the primary testing direction for various products. Therefore, it is imperative that these test specimens be taken from the same sheet, plate, bar, extrusion, forging, or casting. Test specimens shall be located in close proximity. If coupons or specimens are machined prior to heat treatment, all specimens representing a lot shall be heat treated simultaneously in the same heat treat load through all heat treating operations. This procedure is necessary to provide precise mechanical property relationships (ratios).

Table 9.1.6. Test Matrix to Provide Required Mechanical Property Data for Determination of Design Values for Derived Properties (on S-Basis)

Lot Letter[a,b,c]	Test Specimen Requirements												
	TUS & TYS[d,e,f,g]			CYS[d,e,g]			SUS[k]			BUS & BYS[j], e/D = 1.5		BUS & BYS[j], e/D = 2.0	
	L	LT	ST[h]	L	LT	ST[h]	L	LT	ST[h]	L	LT[h]	L	LT[h]
A	2[i]	2	2	2	2	2	2	2	2	2	2	2	2
B	2	2	2	2	2	2	2	2	2	2	2	2	2
C	2	2	2	2	2	2	2	2	2	2	2	2	2
D	2	2	2	2	2	2	2	2	2	2	2	2	2
E	2	2	2	2	2	2	2	2	2	2	2	2	2
F	2	2	2	2	2	2	2	2	2	2	2	2	2
G	2	2	2	2	2	2	2	2	2	2	2	2	2
H	2	2	2	2	2	2	2	2	2	2	2	2	2
I	2	2	2	2	2	2	2	2	2	2	2	2	2
J	2	2	2	2	2	2	2	2	2	2	2	2	2

a Ten lots, representing at least two production heats, or casts or melts, are required.
b Thicknesses of ten lots shall span thickness range of product form covered by material specification.
c For a single lot, multiple heat treat lots shall not be used to meet 10-lot requirement.
d If precision modulus values for E and E_c are not available, precision modulus tests should be conducted on three lots.
e Stress-strain data from at least three lots shall be submitted.
f Full-range tensile stress-strain data from at least one lot shall be submitted, but data from three or more lots are preferred.
g Products should also be tested in the 45° grain direction that are anticipated to have significantly different properties in this direction than the standard grain directions; these include materials such as aluminum-lithium alloys and Aramid fiber reinforced sheet laminate.
h As applicable, depending on product form and size.
i At least two specimens are recommended; however, a single test is acceptable if retesting can be accomplished to replace invalid tests.
j It is recommended that minimum sheet and strip selected for bearing tests comply with the t/D ratio (0.25-0.50) specified in ASTM E238. For failure modes, see Figure 9.4.1.7.2.
k It is recommended that sheet and strip $\geq$0.050 inch in thickness be selected for shear tests conducted according to ASTM B831. Shear testing of sheet <0.050 inch in thickness may result in invalid results due to buckling around the pin hole areas during testing.

Table 9.1.6.2. Definitions of Heat, Melt, and Cast

Material	Heat, Melt, or Cast
Ingot Metallurgy Wrought Products Excluding Aluminum Alloys	A heat is material which, in the case of batch melting, is cast at the same time from the same furnace and is identified with the same heat number; or, in the case of continuous melting, is poured without interruption.
Ingot Metallurgy Wrought Aluminum Alloy Products	A cast consists of the sequential aluminum ingots which are melted from a single furnace charge and poured in one or more drops without changes in the processing parameters. (The cast number is for internal identification and is not reported.)
Powder Metallurgy Wrought Products Including Metal-Matrix Composites	A heat is a consolidated (vacuum hot pressed) billet having a distinct chemical composition.
Cast Alloy Products Including Metal-Matrix Composites	A melt is a single homogeneous batch of molten metal for which all processing has been completed and the temperature has been adjusted and made ready to pour castings. (For metal-matrix composites, the molten metal includes unmelted reinforcements such as particles, fibers, or whiskers.)

Test specimens shall be located within the cross section of the product in accordance with the applicable material specification, or applicable sampling specification, such as AMS 2355, AMS 2370, and AMS 2371. Subsize tensile and compressive test specimens may be used when appropriate.

Test specimens shall be excised in longitudinal, long transverse, and short transverse (when applicable) grain directions. Mechanical properties shall also be obtained in the 45° grain direction for materials that are anticipated to have significantly different properties in this direction than the standard grain directions. For some product configurations, it may be impractical to obtain transverse bearing specimens. For aluminum die forgings, the longitudinal grain direction is defined as orientations parallel, within ±15°, to the predominate grain flow. The long transverse grain direction is defined as perpendicular, within ±15°, to the longitudinal (predominate) grain direction and parallel, within ±15°, to the parting plane. (Both conditions must be met.) The short transverse grain direction is defined as perpendicular, within ±15°, to the longitudinal (predominate) grain direction and perpendicular, within ±15°, to the parting plane. (Both conditions must be met.) All three grain directions are applicable and tests shall be conducted.

Triplicate test specimens are preferred. Single test specimens may be acceptable for some products providing retesting can be performed when needed. Duplicate specimens are recommended as an economical compromise. Some variation in strength within a product is expected. The use of replicate specimens provides multiple mechanical property observations so that lot averages can be used to form paired mechanical property ratios. Mechanical property ratios formed from lot averages are more reliable than those formed from individual observations.

9.1.6.4 *Test Procedures* — All tests shall be performed in accordance with applicable ASTM specifications. The pin shear testing of aluminum alloys is covered by ASTM B 769. Grain orientations and loading directions for shear specimens are also specified in ASTM B 769. Published shear testing standards are not available for aluminum alloy sheet, strip, or thin extrusions or for products from other alloy systems. Bearing tests for products from all alloy systems shall be conducted in accordance with ASTM E 238 using "clean pin" test procedures. For aluminum alloy plate, bearing specimens are oriented flatwise and for aluminum alloy die and hand forgings, bearing specimens are oriented edgewise, as described in Section 3.1.2.1.1.

9.1.6.5 *Mechanical Properties* — Tensile, compression, shear, and bearing tests shall be conducted at room temperature to determine tensile yield and ultimate strengths, compressive yield strength, shear ultimate strength, and bearing yield and ultimate strengths for $e/D = 1.5$ and $e/D = 2.0$ for each grain direction and each lot of material. All data shall be identified by lot, or heat, or melt. For materials used exclusively in high temperature applications, such as gas turbine or rocket engines, the determination of design values for compression, shear, and bearing strengths may be waived by the MIL-HDBK-5 Coordination Group. In lieu of data for these properties, sufficient elevated temperature data for tensile yield and ultimate strengths, as well as modulus of elasticity, shall be submitted so that elevated temperature curves can be constructed. Data should be submitted for the useful temperature range of the product. See Section 9.3.1.1.1 for data requirements for elevated temperature curves.

9.1.6.6 *Modulus of Elasticity Data* — Tensile and compressive modulus of elasticity values shall be determined for at least three lots of material. Elastic modulus values are those obtained using a Class B-1 or better extensometer. The method of determining or verifying the classification of extensometers is identified in ASTM E 83. ASTM E 111 is the standard test method for the determination of Young's Modulus, tangent modulus, and chord modulus of structural materials. A modulus value shall also be obtained for the 45 degree grain orientation for materials that are anticipated to have significantly different properties in this direction than the standard grain directions.

9.1.6.7 *Other Data* — Room temperature, tensile, and compressive load-deformation curves or stress-strain data for each grain direction from at least three lots shall be provided. Room temperature, full-range, tensile load deformation curves or stress-strain data for each grain direction shall also be provided. Full-range stress-strain data shall be provided for at least one lot, but data for three lots are preferable. For heat resistant materials for which elevated temperature data for tensile yield and ultimate strengths are required, room and elevated temperature stress-strain data shall be provided. A precise density value in pounds per cubic inch shall be provided. Although not required, physical property data for coefficient of expansion, thermal conductivity, and specific heat should be submitted, when available. Also, information regarding manufacturing (fabrication and processing), environmental effects (corrosion resistance), heat treat condition and applicable specification shall be provided so that a comments and properties section can be prepared. Also, data for creep, stress rupture, fatigue crack propagation, fatigue and fracture toughness properties should be submitted whenever possible, especially when applicable specifications contain minimum property requirements, such as minimum fracture toughness values.

9.1.6.8 *Guideline Requirements for Specification Minimum Design Mechanical Properties* (S-basis) — A product must be covered by an industry specification prior to being considered for inclusion into MIL-HDBK-5 as indicated in 9.1.6.1. Within a specification, one of the basic requirements is to provide minimum properties (S-basis) which includes tension yield, tension ultimate, elongation and compression yield (when specified). As indicated in Section 9.2.2, the statistical significance to the S-basis properties is typically not known. However, it is known that minimum mechanical properties in the SAE/AMS specifications have been statistically justified in recent years (since ~ 1975) with a procedure contained in their documents. With that in mind, a procedure has been established to provide some level of statistical significance to these S-basis properties contained within the Handbook.

A material being submitted for inclusion into MIL-HDBK-5 shall include as part of the substantiation package the basis of the specification properties. This substantiation package should include the number of test samples, the number of lots, and the method of determining any property covered in the specification even if it is not to be reported in MIL-HDBK-5. This could include the development of minimum as well as maximum properties. Consideration must be made for the specified sizes, product forms, heat treatments and other variables affecting the physical and mechanical properties. It is also expected that the test material chemistry be in the nominal specification range and not tailored to the chemistry extremes.

It is recommended that the substantiation be based on a procedure similar to SAE/AMS in which the analysis of data or other appropriate documentation supports a statistical S-basis value where at least 99 percent of the population of values is expected to equal or exceed the minimum value with a confidence of 95 percent. Since only limited quantities of data are generally available for the basic mechanical properties (tension yield, tension ultimate, compression yield), it is recommended that at least 30 test samples from at least three heats or lots of material are provided for each thickness range or product form. The S-basis value may be computed by assuming the distribution of the sample population to be normal and using the following equation:

$$\text{Minimum S} = \bar{X} - s \cdot k_{99} \qquad (9.1.6.8)$$

where

$\bar{X}$ = sample mean

s = standard deviation

k_{99} = one-sided tolerance-limit factor corresponding to a proportion at least 0.99 of a normal distribution and a confidence coefficient of 0.95 based on the number of specimens (See Table 9.6.4.1).

When the tensile and compressive properties vary significantly with thickness, regression analysis should be used.

Although the establishment of an S-basis value should be based upon the statistically computed value, the S-basis value may be slightly lower, based on experience and judgement, to insure conservative values.

9.1.7 PROCEDURE FOR THE SUBMISSION OF MECHANICAL PROPERTY DATA — This section specifies the procedure for submission of mechanical property data for statistical analysis; specifically data supplied for the determination of T_{99} and T_{90} values for F_{tu} and F_{ty} and for data supplied to obtain derived property values for F_{cy}, F_{su}, F_{bru} and F_{bry}. The amount of data to be supplied for both of these are indicated in other sections of Chapter 9, such as Table 9.1.6 for derived property values. This section covers the format to submit the data in electronic form.

9.1.7.1 *Computer Software* — The data can be supplied on 3.5 or 5.25 inch disks for PC format or on 3.5 inch disks for Macintosh format. It is recommended that the software applications in Table 9.1.7.1 be used to construct the data files. Along with the floppy disk, provide a hard (paper) copy of the data contained on the disk and any other supporting documentation such as specimen dimensions, gage length etc. This information will be stored in the MIL-HDBK-5 archives for future reference.

Table 9.1.7.1. Software Applications for Data Submission

ASCII text editor
- Current Spreadsheet or Database Applications
- The Chairman or Secretary of MIL-HDBK-5 can be contacted concerning software compatibility questions.

The data supplied on these disks are to be supplied in English units. For example, physical dimensions should be reported in units of inches to the nearest thousandth of an inch (X.XXX), stress should be reported in units of ksi to the nearest one hundredth of a ksi (X.XX), strain is to be reported in percent to the nearest tenth of a percent (X.X) and modulus is to be reported in units of 10^3 ksi to the nearest tenth of a msi (X.X). If necessary, refer to Table 1.2.2 to convert to English units of measure.

9.1.7.2 *General Data Format* — Tables 9.1.7.2(a) and (b), for wrought and cast products respectively, show the information that should be supplied in electronic form along with the mechanical test results. The columns (or data fields), in order, will contain alloy type, specification number, temper/heat treatment, lot and/or heat number, product form, product thickness, specimen location, grain direction, and specimen number. Columns will be added towards the right of the specimen number and will contain the individual test results as discussed in Sections 9.1.7.3 and 9.1.7.4.

When specifying grain direction for wrought product strengths, etc., use the conventions identified in Table 9.1.6: L for longitudinal, LT for long transverse, and ST for short transverse. Products that are anticipated to have significantly different properties in directions other than those stated above should be tested in the appropriate directions and the results reported.

There are several types of product forms identified in the Handbook; therefore, the term product form should be properly defined and reported in this column. Examples for wrought products are sheet, plate, bar, and forging. Examples for cast products are sand casting , investment casting, and permanent mold casting. For cast products it is important to identify properties from designated or nondesignated areas.

9.1.7.3 *Data Format for the Determination of A and B-Basis Values of F_{tu} and F_{ty}* — The tensile test results that are to be reported for determination of A and B-basis properties are tensile ultimate strength (TUS), tensile yield strength (TYS), elongation (e), reduction of area (RA), and modulus. The results of these tests are to be reported as shown in Table 9.1.7.3 along with alloy designation, specification, lot and/or heat number, product thickness, grain direction, etc. as previously shown in Table 9.1.7.2. The number of tests required for determining A and B-basis properties are identified in Section 9.2.

9.1.7.4 *Data Format for Derived Property Values* — For the derived property values, several types of tests may be conducted such as tensile, compression, shear and bearing, as shown in Table 9.1.6. The results of these tests are to be reported as shown in Table 9.1.7.4 along with alloy designation, specification, lot and/or heat number, product thickness, grain direction, etc. as previously shown in Table 9.1.7.2. The ultimate strength properties are to be contained in one file as shown in Table 9.1.7.4(a) while the yield strength properties are to be contained in another file as shown in Table 9.1.7.4(b).

Generally, two tests are preferred (one required) for a given test type and product thickness. The results of these tests are to be reported in columns adjacent to each other. For example, TUS Test #1 and TUS Test #2 are on the same row for a given thickness and heat. An additional column should be created to report the specimen number for the second test. This column should be just to the left of the test result. The same procedure is to be used for the other properties. The abbreviations (see Section 1.2.2) for the other test types are CYS for compressive yield, SUS for shear ultimate, and BUS and BYS for bearing ultimate and bearing yield strengths, respectively. For the bearing properties, also identify the e/D ratio of either 1.5 or 2.0.

9.1.7.5 *Data Format for the Construction of Typical Stress-Strain Curves* — The tensile and compression stress-strain data should also be submitted in electronic form, if possible, so that typical tensile and compression stress-strain curves, compression tangent-modulus and typical tensile (full-range) curves can be constructed. In order to construct a typical stress-strain curve, the individual specimen curves must be documented up to slightly beyond the 0.2 percent offset yield strength. To construct a typical (full-range) stress-strain curve, the individual curves must be documented through to failure.

The data for the stress-strain curves must be supplied on a separate floppy disk from the mechanical property data. The data should be stored in a file which contains the load (or stress) in the first column and the displacement (or strain) in the second column. Each stress-strain pair should be identified with its corresponding specimen identification number.

For the load-displacement curves, the load should be reported in pounds (X.) and the displacement should be reported in units of thousandth of an inch (X.XXX). For stress-strain curves, the stress should be reported to the nearest hundredth of a ksi (X.XX) and strain should be reported to the nearest X.XX x10^{-6} units.

A hard copy of the load displacement curve should also be submitted for each stress-strain curve.

Table 9.1.7.2(a). General Data Format for Wrought Products

Alloy Trade Name	Industry/ Government Specification No.	Temper/Heat Treatment	Lot and/or Heat No.	Product Form	Product Thickness (in.), or Area (in.^{2})	Speci-men Location	Grain Direc-tion	Specimen No.

Table 9.1.7.2(b). General Data Format for Cast Products

Alloy Trade Name	Industry/ Government Specification No.	Temper/Heat Treatment	Lot and/or Heat No.	Product Form	Product Thickness	Specimen Location (Designated, Nondesig-nated)	Specimen No.

Table 9.1.7.3. Data Format for Determination of A and B-Basis Values of F_{tu} and F_{ty}

Alloy Trade Name		Specimen No.	TUS ksi	TYS ksi	% E	% R	Elastic Modulus, msi
	The information to be entered between these two columns						
	depends upon the product form, see Table 9.1.7.2(a) or (b).						

Table 9.1.7.4(a). Derived Ultimate Properties

Alloy Trade Name		Specimen No.	TUS Test 1	TUS Test 2*	SUS Test 1	SUS Test 2*	BUS e/D=1.5 Test 1	BUS e/D=1.5 Test 2*	BUS e/D-2.0 Test 1	BUS e/D=2.0 Test 2*
	The information to be entered between these two									
	columns depends upon the product form, see Table 9.1.7.2(a) or (b).									

* Two tests are preferred, only one is required.

Table 9.1.7.4(b). Derived Yield Properties

Alloy Trade Name		Specimen No.	TYS Test 1	TYS Test 2*	CYS Test 1	CYS Test 2*	BYS e/D=1.5 Test 1	BYS e/D=1.5 Test 2*	BYS e/D-2.0 Test 1	BYS e/D=2.0 Test 2*
	The information to be entered between these two									
	columns depends upon the product form, see Table 9.1.7.2(a) or (b).									

* Two tests are preferred, only one is required.

APPENDIX A

A.0 GLOSSARY

A.1 ABBREVIATIONS (also see Sections 1.2.1, 9.2.2, 9.3.4.3, 9.3.6.2, 9.4.1.2, 9.5.1.2, and 9.6).

a — Amplitude; crack or flaw dimension; measure of flaw size, inches.
a_c — Critical half crack length.
a_o — Initial half crack length.
A — Area of cross section, square inches; ratio of alternating stress to mean stress; subscript "axial"; A basis for mechanical-property values (see Section 1.4.1.1 or Section 9.2.2.1); "A" ratio, loading amplitude/mean load; or area.
A_ϵ — Strain "A" ratio, strain amplitude/mean strain.
A_i — Model parameter.
AD — Anderson-Darling test statistic, computed in goodness-of-fit tests for normality or Weibullness.
AISI — American Iron and Steel Institute.
AMS — Aerospace Materials Specification (published by Society of Automotive Engineers, Inc.).
Ann — Annealed.
AN — Air Force-Navy Aeronautical Standard.
ASTM — American Society for Testing and Materials.
b — Width of sections; subscript "bending".
br — Subscript "bearing".
B — Biaxial ratio (see Equation 1.3.2.8); B-basis for mechanical-property values (see Section 1.4.1.1 or Section 9.2.2.1).
Btu — British thermal unit(s).
BUS — Individual or typical bearing ultimate strength.
BYS — Individual or typical bearing yield strength.
c — Fixity coefficient for columns; subscript "compression".
cpm — Cycles per minute.
C — Specific heat; Celsius; Constant.
CEM — Consumable electrode melted.
CRES — Corrosion resistant steel (stainless steel).
C(T) — Compact tension.
CYS — Individual or typical compressive yield strength.
d — Mathematical operator denoting differential.
D or d — Diameter, or Durbin Watson statistic; hole or fastener diameter; dimpled hole.
df — Degrees of freedom.
e — Elongation in percent, a measure of the ductility of a material based on a tension test; unit deformation or strain; subscript "fatigue or endurance"; the minimum distance from a hole, center to the edge of the sheet; Engineering strain.
e_e — Elastic strain.
e_p — Plastic strain.
e/D — Ratio of edge distance (center of the hole to edge of the sheet) to hole diameter (bearing strength).
E — Modulus of elasticity in tension or compression; average ratio of stress to strain for stress below proportional limit.
E_c — Modulus of elasticity in compression; average ratio of stress to strain below proportional limit.

E_s	—	Secant modulus of elasticity, Eq. 9.3.2.5b.
E_t	—	Tangent modulus of elasticity.
ELI	—	Extra low interstitial (grade of titanium alloy).
ER	—	Equivalent round.
ESR	—	Electro-slag remelted.
f	—	Internal (or calculated) tension stress; stress applied to the gross flawed section; creep stress.
f_b	—	Internal (or calculated) primary bending stress.
f_c	—	Internal (or calculated) compressive stress; maximum stress at fracture: gross stress limit (for screening elastic fracture data).
f_{pl}	—	Proportional limit.
f_s	—	Internal (or calculated) shear stress.
f_t	—	Internal (or calculated) tensile stress.
ft	—	Foot: feet.
F	—	Design stress; Fahrenheit; Ratio of two sample variances.
F_A	—	Design axial stress.
F_b	—	Design bending stress; modulus of rupture in bending.
F_{bru}	—	Design ultimate bearing stress.
F_{bry}	—	Design bearing yield stress.
F_c	—	Design column stress.
F_{cc}	—	Design crushing or crippling stress (upper limit of column stress for local failure).
F_{cu}	—	Design ultimate compressive stress.
F_{cy}	—	Design compressive yield stress at which permanent strain equals 0.002.
F_H	—	Design hoop stress.
F_s	—	Design shear stress.
F_{sp}	—	Design proportional limit in shear.
F_{st}	—	Design modulus of rupture in torsion.
F_{su}	—	Design ultimate stress in pure shear (this value represents the average shear stress over the cross section).
F_{sy}	—	Design shear yield stress.
F_{tp}	—	Design proportional limit in tension.
F_{tu}	—	Design tensile ultimate stress.
F_{ty}	—	Design tensile yield stress at which permanent strain equals 0.002.
g	—	Gram(s).
G	—	Modulus of rigidity (shear modulus).
Gpa	—	Gigapascal(s).
hr	—	Hour(s).
H	—	Subscript “hoop”.
HIP	—	Hot isostatically pressed.
i	—	Slope (due to bending) of neutral plane of a beam, in radians (1 radian = 57.3 degrees).
in.	—	Inch(es).
I	—	Axial moment of inertia.
J	—	Torsion constant (= Ip for round tubes); Joule.
k	—	Tolerance limit factor for the normal distribution and the specified probability, confidence, and degrees of freedom; Strain at unit stress.
k_{99}, k_{90}	—	One-sided tolerance limit factor for T_{99} and T_{90}, respectively (see Section 9.2.7.2).
$k_{A,B}$	—	K to A basis or B basis, respectively (see Section 9.2.7.2).
ksi	—	Kips (1,000 pounds) per square inch.
K	—	A constant, generally empirical; thermal conductivity; stress intensity; Kelvin; correction factor.
K_{app}	—	Apparent plane stress fracture toughness or residual strength.

K_c — Critical plane stress fracture toughness, a measure of fracture toughness at point of crack growth instability.
K_f — Fatigue notch factor, or fatigue strength reduction factor.
K_{Ic} — Plane strain fracture toughness.
K_N — Empirically calculated fatigue notch factor.
K_t — Theoretical stress concentration factor.
lb — Pound.
ln — Natural (base e) logarithm.
log — Base 10 logarithm.
L — Length; subscript "lateral"; longitudinal (grain direction).
LT — Long transverse (grain direction).
m — Subscript "mean"; metre; slope.
mm — Millimeter(s).
M — Applied moment or couple, usually a bending moment.
Mc — Machine countersunk.
Mg — Megagram(s).
MIG — Metal-inert-gas (welding).
MPa — Megapascal(s).
MS — Military Standard.
M.S. — Margin of safety.
M(T) — Middle tension.
n — Number of individual measurements or pairs of measurements; subscript "normal"; cycles applied to failure; shape parameter for the standard stress-strain curve (Ramberg-Osgood parameter); number of fatigue cycles endured.
N — Fatigue life, number of cycles to failure; Newton; normalized.
N_f — Fatigue life, cycles to failure.
N_i* — Fatigue life, cycles to initiation.
N_t* — Transition fatigue life where plastic and elastic strains are equal.
NAS — National Aerospace Standard.
p — Subscript "polar"; subscript "proportional limit".
psi — Pounds per square inch.
P — Load; applied load (total, not unit, load); exposure parameter; probability.
P_a — Load amplitude.
P_m — Mean load.
P_{max} — Maximum load.
P_{min} — Minimum load.
Pu — Test ultimate load, pounds per fastener.
Py — Test yield load, pounds per fastener.
q — Fatigue notch sensitivity.
Q — Static moment of a cross section.
Q&T — Quenched and tempered.
r — Radius; root radius; reduced ratio (regression analysis); ratio of two pair measurements; rank of test point within a sample.
$\bar{r}$ — average ratio of paired measurements.
R — Load (stress) ratio, or residual (observed minus predicted value); stress ratio, ratio of minimum stress to maximum stress in a fatigue cycle; reduced ratio.
R_b — Stress ratio in bending.
R_c — Stress ratio in compression; Rockwell hardness - C scale.

* Different from ASTM.

R_ϵ	—	Strain ratio, $\epsilon_{min}/\epsilon_{max}$.
R_s	—	Stress ratio in shear or torsion; ratio of applied load to allowable shear load.
R_t	—	Ratio of applied load to allowable tension load.
RA	—	Reduction of area.
R.H.	—	Relative humidity.
RMS	—	Root-mean-square (surface finish).
RT	—	Room temperature.
s	—	Estimated population standard deviation; sample standard deviation; subscript “shear”.
s^2	—	Sample variance.
S	—	Shear force; nominal engineering stress, fatigue; S-basis for mechanical-property values (see Section 1.4.1.1).
S_a	—	Stress amplitude, fatigue.
S_e	—	Fatigue limit.
S_{eq}*	—	Equivalent stress.
S_f	—	Fatigue limit.
s_m	—	Mean stress, fatigue.
S_{max}	—	Highest algebraic value of stress in the stress cycle.
S_{min}	—	Lowest algebraic value of stress in the stress cycle.
S_r	—	Algebraic difference between the maximum and minimum stresses in one cycle.
S_y	—	Root mean square error.
SAE	—	Society of Automotive Engineers.
SCC	—	Stress-corrosion cracking.
SEE	—	Estimate population standard error of estimate.
SR	—	Studentized residual.
ST	—	Short transverse (grain direction).
STA	—	Solution treated and aged.
SUS	—	Individual or typical shear ultimate strength.
SYS	—	Individual or typical shear yield strength.
t	—	Thickness; subscript “tension”; exposure time; elapsed time; tolerance factor for the “t” distribution with the specified probability and appropriate degrees of freedom.
T	—	Transverse direction; applied torsional moment; transverse (grain direction); subscript “transverse”.
T_F	—	Exposure temperature.
T_{90}	—	Statistically based lower tolerance bound for a mechanical property such that at least 90 percent of the population is expected to exceed T_{90} with 95 percent confidence.
T_{99}	—	Statistically based lower tolerance bound for a mechanical property such that at least 99 percent of the population is expected to exceed T_{99} with 95 percent confidence.
TIG	—	Tungsten-inert-gas (welding).
TUS	—	Individual or typical tensile ultimate strength.
TUS (S_u)*	—	Tensile ultimate strength.
TYS	—	Individual or typical tensile yield strength.
u	—	Subscript “ultimate”.
U	—	Factor of utilization.
V_{99},V_{90}	—	The tolerance limit factor corresponding to T_{99}, T_{90} for the three-parameter Weibull distribution, based on a 95 percent confidence level and a sample of size n.
W	—	Width of center-through-cracked tension panel; Watt.
$\bar{x}$	—	Distance along a coordinate axis.
x	—	Sample mean based upon n observations.

* Different from ASTM.

X — Value of an individual measurement; average value of individual measurements.
y — Deflection (due to bending) of elastic curve of a beam; distance from neutral axis to given fiber; subscript "yield"; distance along a coordinate axis.
Y — Nondimensional factor relating component geometry and flaw size. See Reference 1.4.12.2.1(a) for values.
z — Distance along a coordinate axis.
Z — Section modulus, I/y.

A.2 SYMBOLS (also see Sections 1.2.1, 9.2.2, 9.3.4.3, 9.3.6.2, 9.4.1.2, 9.5.1.2, and 9.6).

α — (1) Coefficient of thermal expansion, mean; constant. (2) Significance level; probability (risk of erroneously rejecting the null hypothesis (see Section 9.6.2)).
α_{99}, α_{90} — Shape parameter estimates for a T_{99} or T_{90} value based on an assumed three-parameter Weibull distribution.
α_{50} — Shape parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
β — Constant.
β_{99}, β_{90} — Scale parameter estimate for a T_{99} or T_{90} value based on an assumed three-parameter Weibull distribution.
β_{50} — Scale parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
$\Delta\epsilon$ or ϵ_r* — strain range, ϵ_{max} - ϵ_{min}.
$\Delta\epsilon_e$ — Elastic strain range.
$\Delta\epsilon_p$ — Plastic strain range.
ΔS (S_r)* — Stress range.
$\Delta\sigma$ — True or local stress range.
ϵ — True or local strain.
ϵ_{eq}* — Equivalent strain.
ϵ_m — Mean strain, $(\epsilon_{max} + \epsilon_{min})/2$.
ϵ_{max} — Maximum strain.
ϵ_{min} — Minimum strain.
ϵ_t — Total (elastic plus plastic) strain at failure determined from tensile stress-strain curve.
δ — Deflection.
Φ — Angular deflection.
ρ — Radius of gyration; Neuber constant (block length).
μ — Poisson's ratio.
σ — True or local stress; or population standard deviation.
σ_x — Population standard deviation of x.
σ_x^2 — Population variance of x.
τ_{99}, τ_{90} — Threshold estimates for a T_{99} or T_{90} value based on an assumed three-parameter Weibull distribution.
τ_{50} — Threshold estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
ω — Density; flank angle.
∞ — Infinity.
Σ — The sum of.
$'$ — Superscript that denotes value determined by regression analysis.

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* Different from ASTM.

A.3 DEFINITIONS (also see Sections 1.2.1, 9.2.2, 9.3.6.2, 9.4.1.2, 9.5.1.2 and 9.6).

A-Basis.—The lower of either a statistically calculated number, or the specification minimum (S-basis). The statistically calculated number indicates that at least 99 percent of the population of values is expected to equal or exceed the A-basis mechanical design property, with a confidence of 95 percent.

Alternating Load.—See Loading Amplitude.

B-Basis.—At least 90 percent of the population of values is expected to equal or exceed the B-basis mechanical property allowable, with a confidence of 95 percent.

Cast.—Cast consists of the sequential ingots which are melted from a single furnace change and poured in one or more drops without changes in the processing parameters. (The cast number is for internal identification and is not reported.) (See Table 9.1.6.1).

Casting.—One or more parts which are melted from a single furnace change and poured in one or more molds without changes in the processing parameters. (The cast number is for internal identification and is not reported.) (See Table 9.1.6.1).

Confidence.—A specified degree of certainty that at least a given proportion of all future measurements can be expected to equal or exceed the lower tolerance limit. Degree of certainty is referred to as the confidence coefficient. For MIL-HDBK-5, the confidence coefficient is 95 percent which, as related to design properties, means that, in the long run over many future samples, 95 percent of conclusions regarding exceedance of A and B-values would be true.

Confidence Interval.—An interval estimate of a population parameter computed so that the statement "the population parameter lies in this interval" will be true, on the average, in a stated proportion of the times such statements are made.

Confidence Interval Estimate.—Range of values, computed with the sample that is expected to include the population variance or mean.

Confidence Level (or Coefficient).—The stated portion of the time the confidence interval is expected to include the population parameter.

*Confidence Limits**.—The two numeric values that define a confidence interval.

Constant-Amplitude Loading.—A loading in which all of the peak loads are equal and all of the valley loads are equal.

Constant-Life Fatigue Diagram.—A plot (usually on Cartesian coordinates) of a family of curves, each of which is for a single fatigue life, N—relating S, S_{max}, and/or S_{min} to the mean stress, S_m. Generally, the constant life fatigue diagram is derived from a family of S/N curves, each of which represents a different stress ratio (A or R) for a 50 percent probability of survival. NOTE—MIL-HDBK-5 no longer presents fatigue data in the form of constant-life diagrams.

Creep.—The time-dependent deformation of a solid resulting from force.

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* Different from ASTM.

Note 1—Creep tests are usually made at constant load and temperature. For tests on metals, initial loading strain, however defined, is not included.

Note 2—This change in strain is sometimes referred to as creep strain.

Creep-Rupture Curve.—Results of material tests under constant load and temperature; usually plotted as strain versus time to rupture. A typical plot of creep-rupture data is shown in Figure 9.3.6.2. The strain indicated in this curve includes both initial deformation due to loading and plastic strain due to creep.

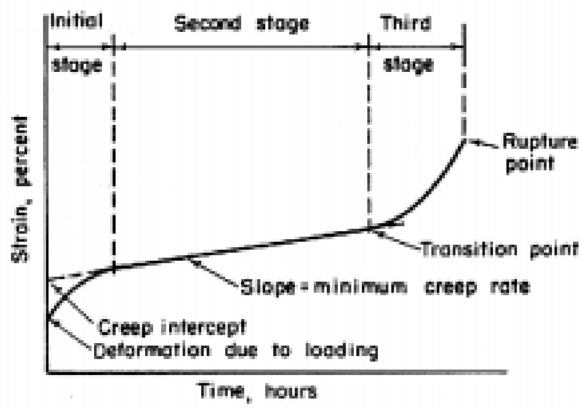

Figure A.1. Typical creep-rupture curve.

Creep-Rupture Strength.—Stress that will cause fracture in a creep test at a given time, in a specified constant environment. Note: This is sometimes referred to as the stress-rupture strength.

Creep-Rupture Test.—A creep-rupture test is one in which progressive specimen deformation and time for rupture are measured. In general, deformation is much larger than that developed during a creep test.

Creep-Strain.—The time-dependent part of the strain resulting from stress, excluding initial loading strain and thermal expansion.

Creep Strength.—Stress that causes a given creep in a creep test at a given time in a specified constant environment.

Creep Stress.—The constant load divided by the original cross-sectional area of the specimen.

Creep Test.—A creep test has the objective of measuring deformation and deformation rates at stresses usually well below those which would result in fracture during the time of testing.

Critical Stress Intensity Factor.—A limiting value of the stress intensity factor beyond which continued flaw propagation and/or fracture may be expected. This value is dependent on material and may vary with type of loading and conditions of use.

Cycle.—Under constant-amplitude loading, the load varies from the minimum to the maximum and then to the minimum load (see Figure 9.3.4.3). The symbol n or N (see definition of fatigue life) is used to indicate the number of cycles.

Deformable Shank Fasteners.—A fastener whose shank is deformed in the grip area during normal installation processes.

Degree of Freedom.—Number of degrees of freedom for n variables may be defined as number of variables minus number of constraints between them. Since the standard deviation calculation contains one fixed value (the mean) it has n - 1 degrees of freedom.

Degrees of Freedom.—Number of independent comparisons afforded by a sample.

Discontinued Test.—See Runout.

Elapsed Time.—The time interval from application of the creep stress to a specified observation.

Fatigue.—The process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points, and which may culminate in cracks or complete fracture after a sufficient number of fluctuations. NOTE—fluctuations in stress and in time (frequency), as in the case of "random vibration".

Fatigue Life.—N—the number of cycles of stress or strain of a specified character that a given specimen sustains before failure of a specified nature occurs.

Fatigue Limit.—S_f—the limiting value of the median fatigue strength as N becomes very large. NOTE—-Certain materials and environments preclude the attainment of a fatigue limit. Values tabulated as "fatigue limits" in the literature are frequently (but not always) values of S_N for 50 percent survival at N cycles of stress in which $S_m = 0$.

Fatigue Loading.—Periodic or non-periodic fluctuating loading applied to a test specimen or experienced by a structure in service (also known as cyclic loading).

*Fatigue Notch Factor**.—The fatigue notch factor, K_f (also called fatigue strength reduction factor), is the ratio of the fatigue strength of a specimen with no stress concentration to the fatigue strength of a specimen with a stress concentration at the same number of cycles for the same conditions. NOTE—In specifying K_f, it is necessary to specify the geometry, mode of loading, and the values of S_{max}, S_m, and N for which it is computed.

Fatigue Notch Sensitivity.—The fatigue notch sensitivity, q, is a measure of the degree of agreement between K_f and K_t. NOTE—the definition of fatigue notch sensitivity is $q = (K_f - 1)/(K_t - 1)$.

Heat.—All material identifiable to a single molten metal source. (All material from a heat is considered to have the same composition. A heat may yield one or more ingots. A heat may be divided into several lots by subsequent processing.)

Heat.—Heat is material which, in the case of batch melting, is cast at the same time from the same furnace and is identified with the same heat number; or, in the case of continuous melting, is poured without interruption. (See Table 9.1.6.2)

Heat.—Heat is a consolidated (vacuum hot pressed) billet having a distinct chemical composition. (See Table 9.1.6.2)

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* Different from ASTM.

Hysteresis Diagram.—The stress-strain path during a fatigue cycle.

Isostrain Lines.—Lines representing constant levels of creep.

Isothermal Lines.—Lines of uniform temperature on a creep or stress-rupture curve.

*Interrupted Test**.—Tests which have been stopped before failure because of some mechanical problem, e.g., power failure, load or temperature spikes.

Loading Amplitude.—The loading amplitude, P_a, S_a, or ϵ_a represents one-half of the range of a cycle (see Figure 9.3.4.3). (Also known as alternating load, alternating stress, or alternating strain.)

Loading Strain.—Loading strain is the change in strain during the time interval from the start of loading to the instant of full-load application, sometimes called initial strain.

Loading (Unloading) Rate.—The time rate of change in the monotonically increasing (decreasing) portion of the load-time function.

Load Ratio.—The load ratio, R, A, or R_ϵ, A_ϵ, or R_σ, A_σ, is the algebraic ratio of the two loading parameters of a cycle; the two most widely used ratios are

$$R = \frac{\text{minimum load}}{\text{maximum load}} = \frac{P_{min}}{P_{max}}$$

or

$$R_\sigma = \frac{S_{min}}{S_{max}}$$

or

$$R_\epsilon = \epsilon_{min}/\epsilon_{max}$$

and

$$A = \frac{\text{loading amplitude}}{\text{mean load}} = \frac{P_a}{P_m} \text{ or } \frac{S_a}{S_M}$$

$$A_\epsilon = \frac{\text{strain amplitude}}{\text{mean strain}} = \frac{\epsilon_a}{\epsilon_M} \text{ or } (\epsilon_{max} - \epsilon_{min})/(\epsilon_{max} + \epsilon_{min}) \quad .$$

NOTE—load ratios R or R_ϵ are generally used in MIL-HDBK-5.

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* Different from ASTM.

Longitudinal Direction.—Parallel to the principal direction of flow in a worked metal. For die forgings this direction is within ±15° of the predominate grain flow.

Long-Transverse Direction.—The transverse direction having the largest dimension, often called the "width" direction. For die forgings this direction is within ±15° of the longitudinal (predominate) grain direction and parallel, within ±15°, to the parting plane. (Both conditions must be met.)

Lot.—All material from a heat or single molten metal source of the same product type having the same thickness or configuration, and fabricated as a unit under the same conditions. If the material is heat treated, a lot is the above material processed through the required heat-treating operations as a unit.

Master Creep Equation.—An equation expressing combinations of stress, temperature, time and creep, or a set of equations expressing combinations of stress, temperature and time for given levels of creep.

Master Rupture Equation.—An equation expressing combinations of stress, temperature, and time that cause complete separation (fracture or rupture) of the specimen.

Maximum Load.—The maximum load, P_{max}, S_{max}, ϵ_{max} is the load having the greatest algebraic value.

Mean Load.—The mean load, P_m, is the algebraic average of the maximum and minimum loads in constant-amplitude loading:

$$P_m = \frac{P_{max} + P_{min}}{2}, \text{ or}$$

$$S_m = \frac{S_{max} + S_{min}}{2}, \text{ or}$$

$$\epsilon_m = \frac{\epsilon_{max} + \epsilon_{min}}{2} \quad ,$$

or the integral average of the instantaneous load values.

Median Fatigue Life.—The middlemost of the observed fatigue life values (arranged in order of magnitude) of the individual specimens in a group tested under identical conditions. In the case where an even number of specimens are tested, it is the average of the two middlemost values (based on log lives in MIL-HDBK-5). NOTE 1—The use of the sample median instead of the arithmetic mean (that is, the average) is usually preferred. NOTE 2—In the literature, the abbreviated term "fatigue life" usually has meant the median fatigue life of the group. However, when applied to a collection of data without further qualification, the term "fatigue life" is ambiguous.

Median Fatigue Strength at N Cycles.—An estimate of the stress level at which 50 percent of the population would survive N cycles. NOTE—The estimate of the median fatigue strength is derived from a particular point of the fatigue-life distribution, since there is no test procedure by which a frequency distribution of fatigue strengths at N cycles can be directly observed. That is, one can not perform constant-life tests.

Melt.—Melt is a single homogeneous batch of molten metal for which all processing has been completed and the temperature has been adjusted and made ready to pour castings. (For metal-matrix composites, the molten metal includes unmelted reinforcements such as particles, fibers, or whiskers.) (See Table 9.1.6.2)

Minimum Load.—The minimum load, P_{min}, S_{min}, or ϵ_{min}, is the load having the least algebraic value.

Nominal Hole Diameters.—Nominal hole diameters for deformable shank fasteners shall be according to Table 9.4.1.2(a). When tests are made with hole diameters other than those tabulated, hole sizes used shall be noted in the report and on the proposed joint allowables table.

Nominal Shank Diameter.—Nominal shank diameter of fasteners with shank diameters equal to those used for standard size bolts and screws (NAS 618 sizes) shall be the decimal equivalents of stated fractional or numbered sizes. These diameters are those listed in the fourth column of Table 9.4.1.2. Nominal shank diameters for nondeformable shank blind fasteners are listed in the fifth column of Table 9.4.1.2. Nominal shank diameters for other fasteners shall be the average of required maximum and minimum shank diameters.

Nondeformable Shank Fasteners.—A fastener whose shank does not deform in the grip area during normal installation processes.

*Outlier**—An experimental observation which deviates markedly from other observations in the sample. An outlier is often either an extreme value of the variability in the data, or the result of gross deviation in the material or experimental procedure.

Peak.—The point at which the first derivative of the load-time history changes from a positive to a negative sign; the point of maximum load in constant-amplitude loading (see Figure 9.3.4.3).

Plane Strain.—The stress state in which all strains occur only in the principal loading plane. No strains occur out of the plane, i.e., $\epsilon_z = 0$, and $\sigma_z \neq 0$.

Plane Stress.—The stress state in which all stresses occur only in the principal loading plane. No stresses occur out of the plane, i.e., $\sigma_z = 0$, and $\epsilon_z \neq 0$.

Plastic Strain During Loading.—Plastic strain during loading is the portion of the strain during loading determined as the offset from the linear portion to the end of a stress-strain curve made during load application.

Plane-Strain Fracture Toughness.—A generic term now generally adopted for the critical plane-strain stress intensity factor characteristic of plane-strain fracture, symbolically denoted K_{Ic}. This is because in current fracture testing practices, specification of the slowly increasing load test of specimen materials in the plane-strain stress state and in opening mode (I) has been dominant.

Plane-Stress and Transitional Fracture Toughness.—A generic term denoting the critical stress intensity factor associated with fracture behavior under nonplane-strain conditions. Because of plasticity effects and stable crack growth which can be encountered prior to fracture under these conditions, designation of a specific value is dependent on the stage of crack growth detected during testing. Residual strength or apparent fracture toughness is a special case of plane-stress and transitional fracture toughness wherein the reference crack length is the initial pre-existing crack length and subsequent crack growth during the test is neglected.

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* Different from ASTM.

Population.—All potential measurements having certain independent characteristics in common; i.e., “all possible TUS(L) measurements for 17-7PH stainless steel sheet in TH1050 condition”.

Precision.*—The degree of mutual agreement among individual measurements. Relative to a method of test, precision is the degree of mutual agreement among individual measurements made under prescribed like conditions. The lack of precision in a measurement may be characterized as the standard deviation of the errors in measurement.

Primary Creep.—Creep occurring at a diminishing rate, sometimes called initial stage of creep.

Probability.—Ratio of possible number of favorable events to total possible number of equally likely events. For example, if a coin is tossed, the probability of heads is one-half (or 50 percent) because heads can occur one way and the total possible events are two, either heads or tails. Similarly, the probability of throwing a three or greater on a die is 4/6 or 66.7 percent. Probability, as related to design allowables, means that chances of a material-property measurement equaling or exceeding a certain value (the one-sided lower tolerance limit) is 99 percent in the case of a A-basis value and 90 percent in the case of a B-basis value.

Range.—Range, ΔP, S_r, $\Delta\epsilon$, ϵ_r, $\Delta\sigma$ is the algebraic difference between successive valley and peak loads (positive range or increasing load range) or between successive peak and valley loads (negative range or decreasing load range), see Figure 9.3.4.3. In constant-amplitude loading, for example, the range is given by $\Delta P = P_{max} - P_{min}$.

Rate of Creep.—The slope of the creep-time curve at a given time determined from a Cartesian plot.

Residual.*—The difference between the observed fatigue (log) life and the fatigue (log) life estimated from the fatigue model at a particular stress/strain level.

Runout.*—A test that has been terminated prior to failure. Runout tests are usually stopped at an arbitrary life value because of time and economic considerations. NOTE—Runout tests are useful for estimating a pseudo-fatigue-limit for a fatigue data sample.

Sample.—A finite number of observations drawn from the population.

Sample.—The number of specimens selected from a population for test purposes. NOTE—The method of selecting the sample determines the population about which statistical inferences or generalization can be made.

Sample Average (Arithmetic Mean).—The sum of all the observed values in a sample divided by the sample size (number). It is a point estimate of the population mean.

Sample Mean.—Average of all observed values in the sample. It is an estimate of population mean. A mean is indicated by a bar over the symbol for the value observed. Thus, the mean of n observations of TUS would be expressed as:

$$\overline{TUS} = \frac{TUS_1 + TUS_2 + \ldots + TUS_n}{n} = \frac{\sum_{i=1}^{n} (TUS_i)}{n}$$

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* Different from ASTM.

Sample Median.—Value of the middle-most observation. If the sample is nearly normally distributed, the sample median is also an estimate of the population mean.

Sample Median.—The middle value when all observed values in a sample are arranged in order of magnitude if an odd number of samples are tested. If the sample size is even, it is the average of the two middlemost values. It is a point estimate of the population median, or 50 percentile point.

Sample Point Deviation.—The difference between an observed value and the sample mean.

Sample Standard Deviation.*—The standard deviation of the sample, s, is the square root of the sample variance. It is a point estimate of the standard deviation of a population, a measure of the "spread" of the frequency distribution of a population. NOTE—This value of s provides a statistic that is used in computing interval estimates and several test statistics.

Sample Variance.*—Sample variance, s^2, is the sum of the squares of the differences between each observed value and the sample average divided by the sample size minus one. It is a point estimate of the population variance. NOTE—This value of s^2 provides both an unbiased point estimate of the population variance and a statistic that is used on computing the interval estimates and several test statistics. Some texts define s^2 as “the sum of the squared differences between each observed value and the sample average divided by the sample size”, however, this statistic underestimates the population variance, particularly for small sample sizes.

Sample Variance.—The sum of the squared deviations, divided by n - 1, and, based on n observations of TUS, expressed as

$$S_{TUS}^{2} = \frac{\sum_{i=1}^{n}\left(TUS_i - \overline{TUS}\right)^2}{n - 1} = \frac{n\sum_{i=1}^{n}(TUS_i)^2 - \left(\sum_{i=1}^{n} TUS_i\right)^2}{n(n - 1)}$$

S-Basis.—The S-value is the minimum property value specified by the governing industry specification (as issued by standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. (See MIL-STD-970 for order of preference for specifications.) For certain products heat treated by the user (for example, steels hardened and tempered to a designated F_{tu}), the S-value may reflect a specified quality-control requirement. Statistical assurance associated with this value is not known.

Secondary Creep.—Creep occurring at a constant rate, sometimes called second stage creep.

Short-Transverse Direction.—The transverse direction having the smallest dimension, often called the “thickness” direction. For die forgings this direction is within ±15° of the longitudinal (predominate) grain direction and perpendicular, within ±15°, to the parting plane. (Both conditions must be met.) When possible, short transverse specimens shall be taken across the parting plane.

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* Different from ASTM.

Significance Level (As Used Here).—Risk of concluding that two samples were drawn from different populations when, in fact, they were drawn from the same population. A significance level of $\alpha = 0.05$ is employed through these Guidelines.*

Significance Level.—The stated probability (risk) that a given test of significance will reject the hypothesis that a specified effect is absent when the hypothesis is true.

Significant (Statistically Significant).—An effect or difference between populations is said to be present if the value of a test statistic is significant, that is, lies outside of predetermined limits. NOTE—An effect that is statistically significant may not have engineering importance.

S/N Curve for 50 Percent Survival.**—A curve fitted to the median values of fatigue life at each of several stress levels. It is an estimate of the relationship between applied stress and the number of cycles-to-failure that 50 percent of the population would survive. NOTE 1—This is a special case of the more general definition of S/N curve for P percent survival. NOTE 2—In the literature, the abbreviated term "S/N Curve" usually has meant either the S/N curve drawn through the mean (averages) or through the medians (50 percent values) for the fatigue life values. Since the term "S/N Curve" is ambiguous, it should be used only when described appropriately. NOTE 3—Mean S/N curves (based on log lives) are shown in MIL-HDBK-5.

S/N Diagram.—A plot of stress against the number of cycles to failure. The stress can be S_{max}, S_{min}, or S_a. The diagram indicates the S/N relationship for a specified value of S_m, A, or R and a specified probability of survival. Typically, for N, a log scale (base 10) is used. Generally, for S, a linear scale is used, but a log scale is used occasionally. NOTE—S_{max}-versus-log N diagrams are used commonly in MIL-HDBK-5.

Standard Deviation.—An estimate of the population standard deviation; the square root of the variance, or

$$S_{TUS} = \sqrt{\frac{\sum_{i=1}^{n}\left(TUS_i - \overline{TUS}\right)^2}{n-1}} = \frac{\sqrt{n\sum_{i=1}^{n}\left(TUS_i\right)^2 - \sum_{i=1}^{n}\left(TUS_i\right)^2}}{n(n-1)}$$

Stress Intensity Factor.—A physical quantity describing the severity of a flaw in the stress field of a loaded structural element. The gross stress in the material and flaw size are characterized parametrically by the stress intensity factor,

$$K = f\sqrt{a}\ Y,\ \text{ksi} - \text{in.}^{1/2} \qquad [9.5.1.2]$$

Stress-Rupture Test—A stress-rupture test is one in which time for rupture is measured, no deformation measurement being made during the test.

Tertiary Creep.—Creep occurring at an accelerating rate, sometimes called third stage creep.

Theoretical Stress Concentration Factor (or Stress Concentration Factor).—This factor, K_t, is the ratio of the nominal stress to the greatest stress in the region of a notch (or other stress concentrator) as determined

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* This is appropriate, since a confidence level of $1 - \alpha = 0.95$ is used in establishing A and B-values.

** Different from ASTM.

by the theory of elasticity (or by experimental procedures that give equivalent values). NOTE—The theory of plasticity should not be used to determine K_t.

Tolerance Interval.—An interval computed so that it will include at least a stated percentage of the population with a stated probability.

Tolerance Level.—The stated probability that the tolerance interval includes at least the stated percentage of the population. It is not the same as a confidence level, but the term confidence level is frequently associated with tolerance intervals.

Tolerance Limits.—The two statistics that define a tolerance interval. (One value may be "minus infinity" or "plus infinity".)

Total Plastic Strain.—Total plastic strain at a specified time is equal to the sum of plastic strain during loading plus creep.

Total Strain.—Total strain at any given time, including initial loading strain (which may include plastic strain in addition to elastic strain) and creep strain, but not including thermal expansion.

Transition Fatigue Life.*—The point on a strain-life diagram where the elastic and plastic strains are equal.

Transverse Direction.—Perpendicular to the principal direction of flow in a worked metal; may be defined as T, LT or ST.

Typical Basis.—A typical property value is an average value and has no statistical assurance associated with it.

Waveform.—The shape of the peak-to-peak variation of a controlled mechanical test variable (for example, load, strain, displacement) as a function of time.

* Different from ASTM.

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